Recycler Status and Plans

Shekhar Mishra

MID/Beams Division

Fermilab

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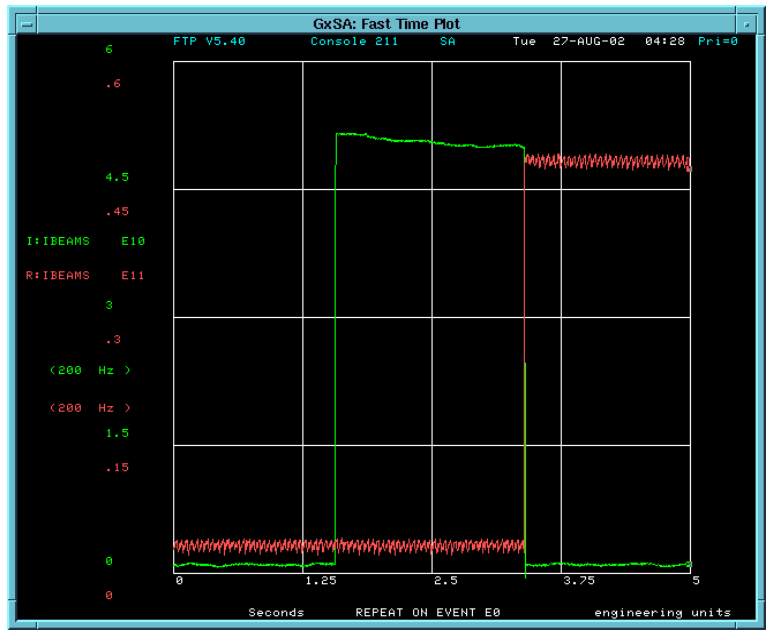
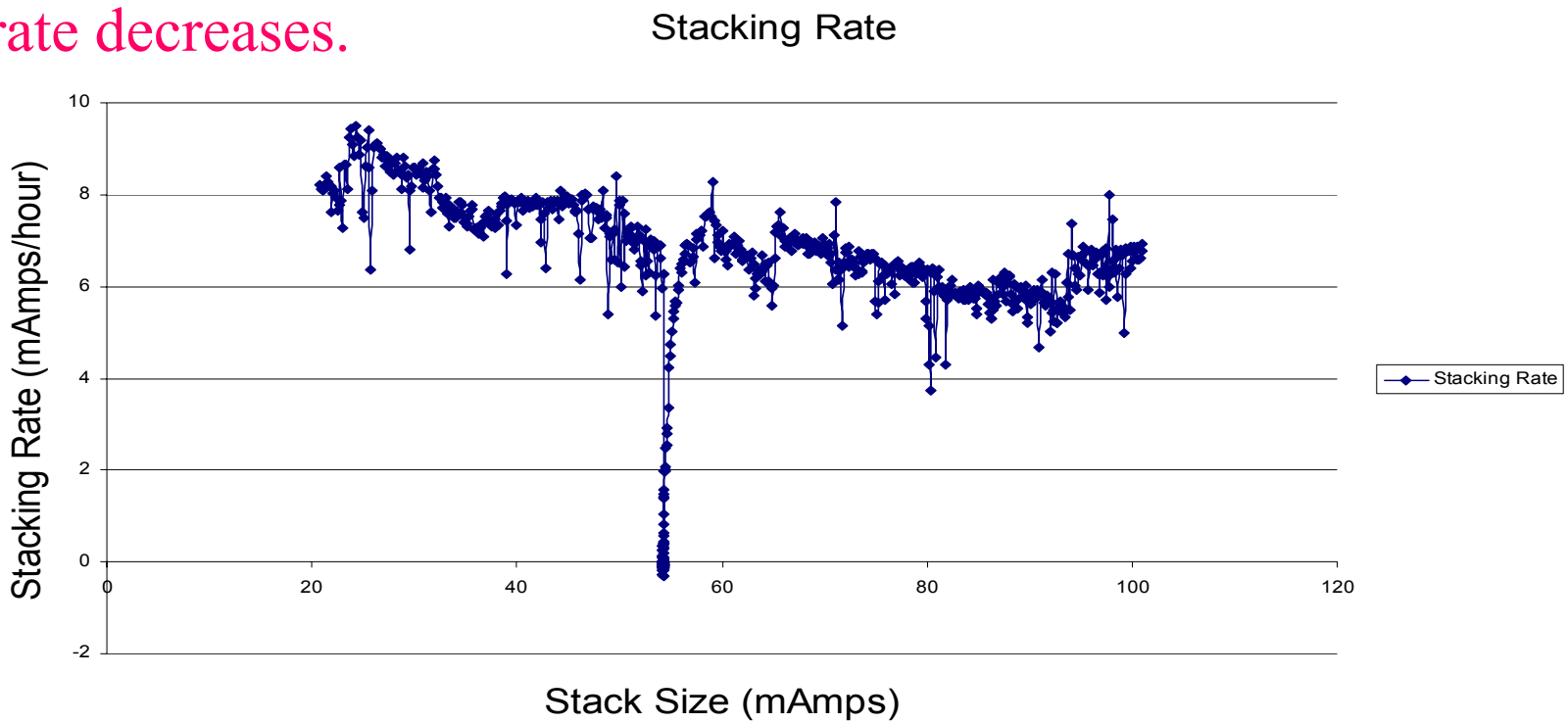
- Introduction to the Recycler Ring
- Work done during several shutdowns
- Study leading to and progress in machine performance after shutdowns
- Present status and upgrade plans
- Summary



Introduction to the Recycler Ring

- The Recycler Ring is designed to store and cool antiprotons at 8.9 GeV/c. In the final configuration it will also Recycler antiproton from the Tevatron at the end of store.

- As the stack size in the Accumulator increases the stacking rate decreases.



Introduction to the Recycler Ring…

- Transfer antiproton from Accumulator to Recycler will be done at small stack sizes, 20-40 e10 to keep the stacking rate in the Accumulator high.
- Recycler antiprotons from the Tevatron at the end of the store (50-70% of pbars are left).
- The Main Injector Project was designed to support a peak luminosity of about 8e31 cm^{-2} sec^{-1} without the Recycler.
- The Recycler is designed to increase this luminosity to 2e32 (5e32) cm^{-2} sec^{-1}.
- Recycler lattice is made up of permanent combined function magnets. The FODO lattice is similar to Main Injector. We have added powered dipole, quadrupole and sextupole correctors.

Recycler Ring…

- The Recycler is designed to store 2-5e12 antiprotons to support the Run-II plans.
- The design lifetime of the Recycler beam is 10 hours without cooling and 100 hours with cooling.
- We have been performing all the RR commissioning using protons from Booster→ MI→RR at 8.9 GeV/c. This is done by using the RR30 transfer line. Proton is extracted out of the Recycler using RR20 line and re-injected into the Main Injector.
- We have done a limited set of antiproton transfer form the Accumulator to the Recycler to tune injection and cooling system.

Recycler Studies

During last two years the Recycler studies have concentrated on the following topics

- Injection
  - Efficiency of protons and antiprotons
  - Emittance growth at injection
  - Aperture
- Recycler Lattice
- Beam Lifetime
- Antiproton transfer to the Recycler
- Commissioning of the cooling system, pbar stacking
- Studies related with planed upgrades

Recycler Upgrades

- Recycler had several construction related problems which has made its commissioning rather time consuming.
- Due to several effects canceling each other (a few we could not comprehend) and lack of proper instrumentations has made it even a longer process.
- Recycler has been upgrades during the following shutdown for improvements.
    - Feb. 00 shutdown
    - Nov. 00 – Jan. 01 shutdown
    - Nov. 01 shutdown
- Recycler design in principle is excellent, due to budget limitation, time pressure and lack of manpower several things were overlooked.

February 2000 Shutdown

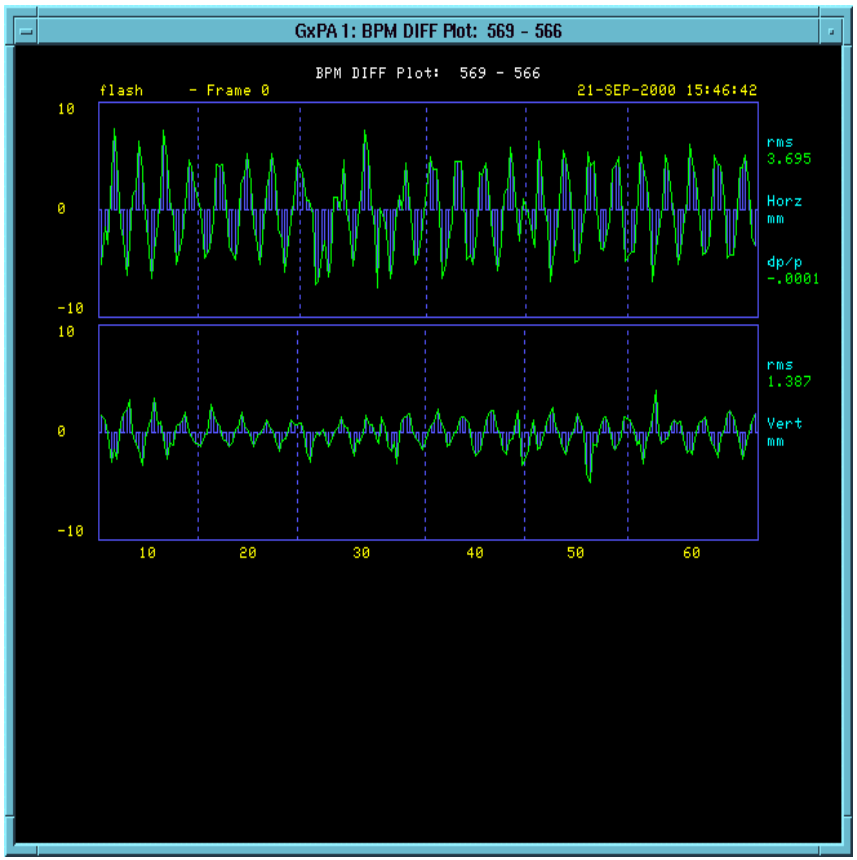
- Recycler End Shim Replacement to properly take into account of sextupole feed down at the end of the combined function magnet.
- Removal of magnetic heater strips. This tape was introducing higher multipoles in the Recyler Magnets, including large sextupole component.
- Realignment of the Recycler magnets. This misalignment happened due to removal of heater tapes.
- Major concern has been loss of ~75% beam in the Recycler in the first 5-10 turns.

February – November 2000

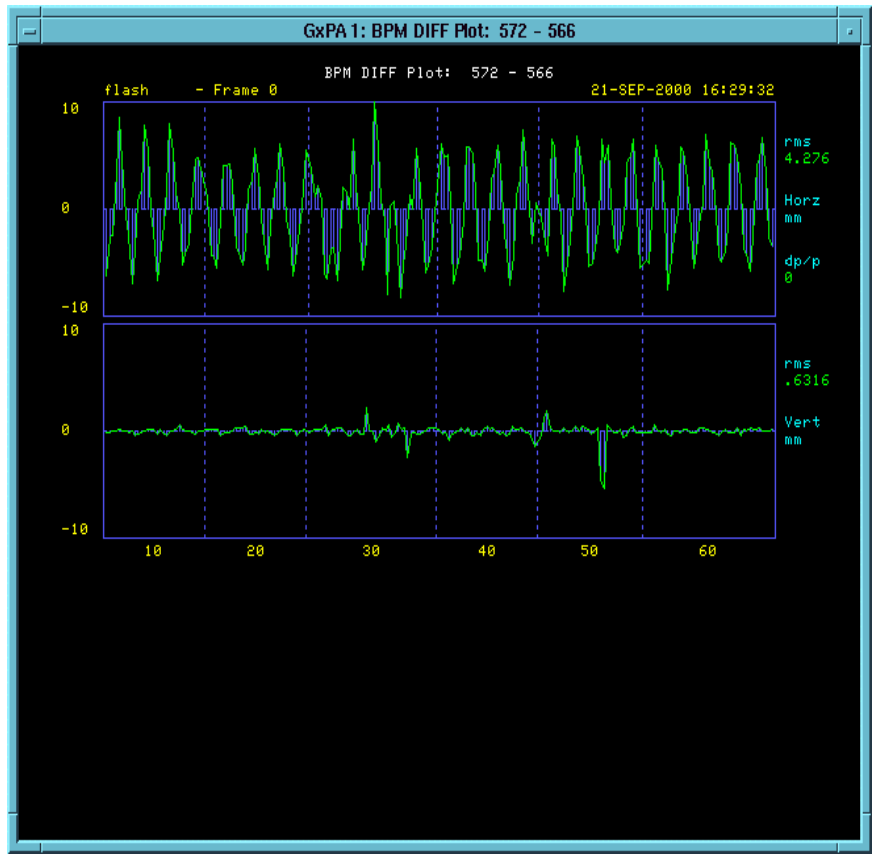
- We made several improvements in the Recycler since Feb 00 shutdown. Most of these work was done in parallel as our understanding of the Recycler progressed.
  - Stable BPM (Beam in MI from 53→ 2.5MHz MI → RR 2.5 MHz)
  - Recycler Injection and orbit
  - Injection orbit coupling (Installation of skew Quad in RR30)
  - Magnet Moves to improve the closed orbit.
  - Closed orbit improvements using correctors. Additional correctors.
  - Alignment of beam pipes and BPM
  - New magnetic Shielding in MI30 straight section
  - Software: injection, orbit, lattice analysis, magnet moves, tune etc
  - Aperture Scan and centering of the beam in Aperture
  - Lattice studies and operating point changes
  - RF manipulations

Decoupling the Injection orbit

We installed two skew quadrupoles in the RR30 transfer line to cancel the effect of skew quadrupole measured in LAM321 and 328.

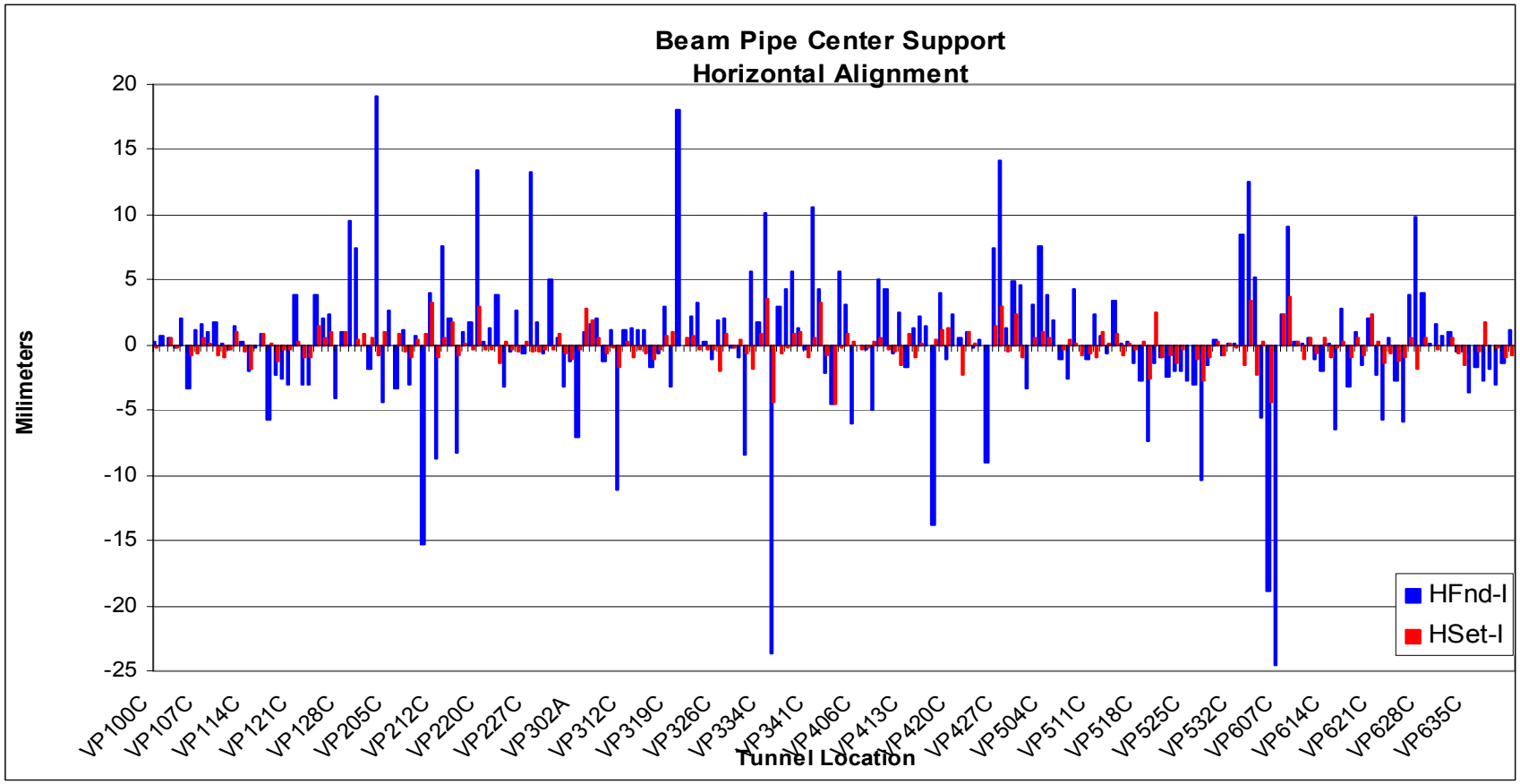


Coupled due to LAM321

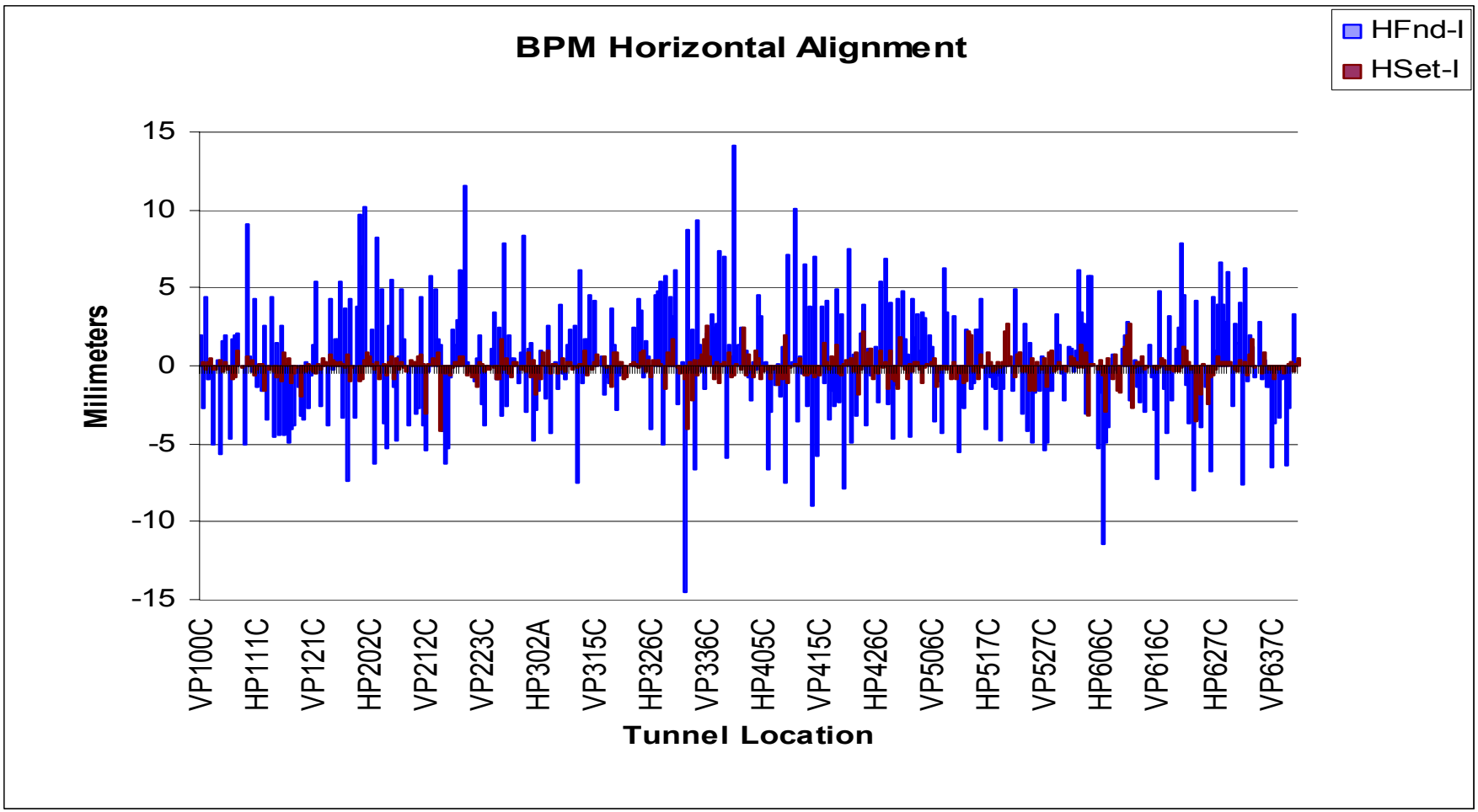


Decoupled by SQ803

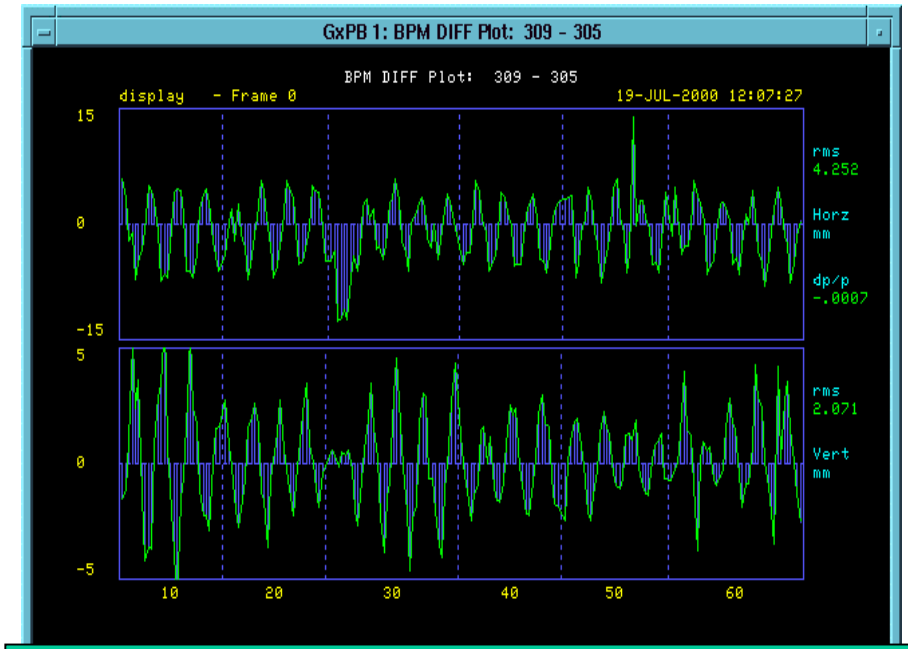
Alignment of Beam Pipe at the Center Support Horizontal

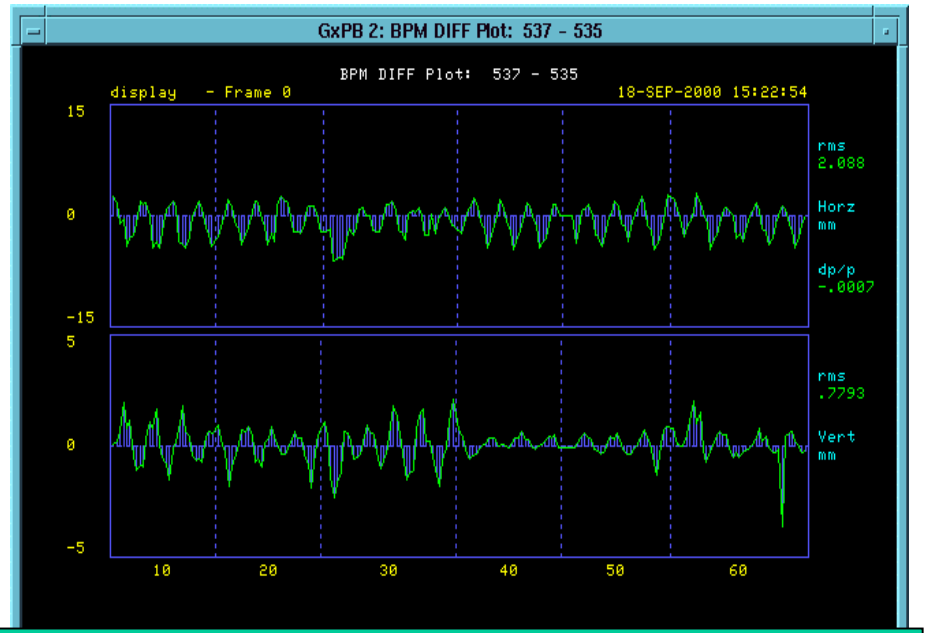


Alignment of the BPM Horizontal



MI Magnetic Field effect on RR orbit





New shielding added in MI30 straight section reduces the effect by a factor of 2.

The MI kick was no longer located at MI30 section of RR.

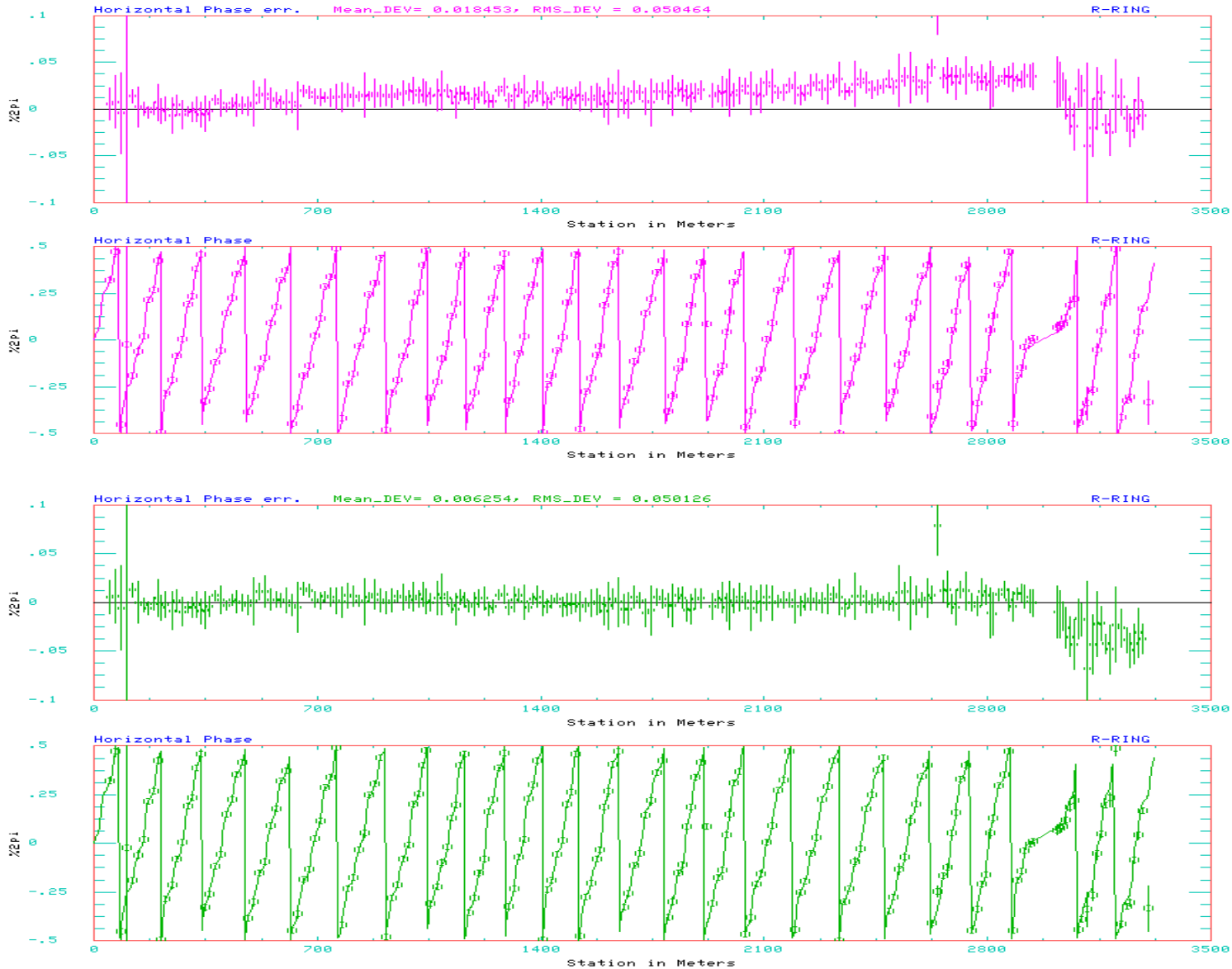
This was due to MI Dipole bus expansion joints.

A R&D on shielding revealed that we needed new mu-metal and rapping technique. Old shielding was not very effective.

Understanding the Recycler Lattice

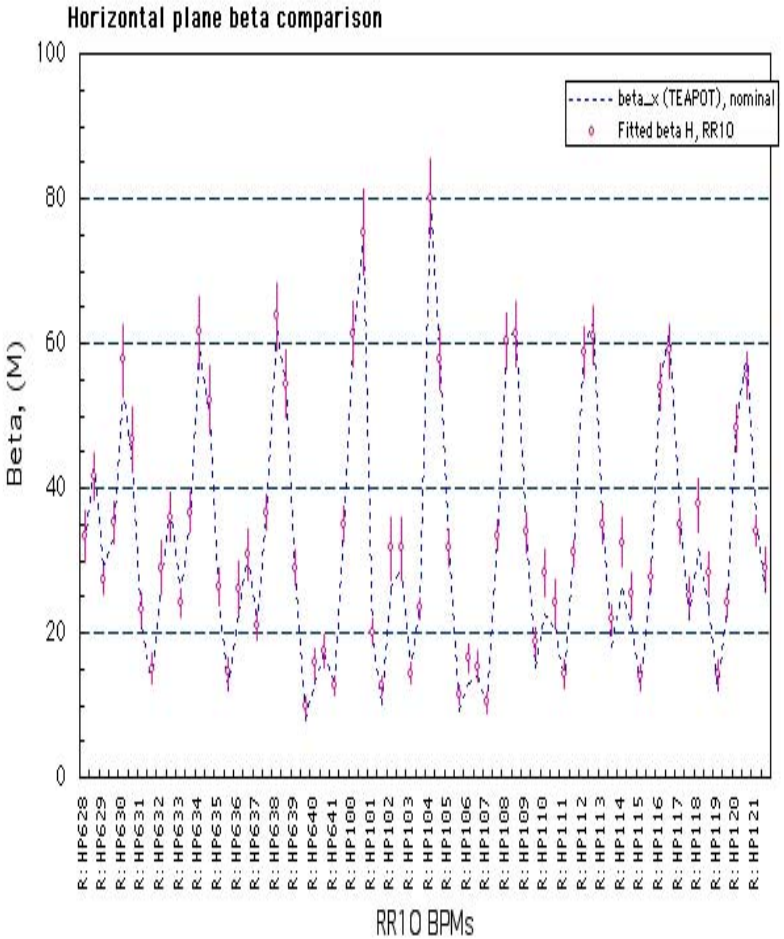
- Main Injector Department constructed a detailed lattice of the Recycler V20. This included all the measured magnetic properties of each magnet installed in the tunnel.
- An Online Physics Analysis software was developed by MID to compare the beam data to theory in a realistic fashion.
- The injection orbit had a very small lattice error till the beam passed through the high beta insert. The phase advance error is with in the magnet specification.
- The Circulating beam beta function error was larger than 40%
- Calculations and measurements pointed the magnetic error to the high beta insert location. This lead to our proposal to replace the high beta insert with the needed insert for the electron cooling.

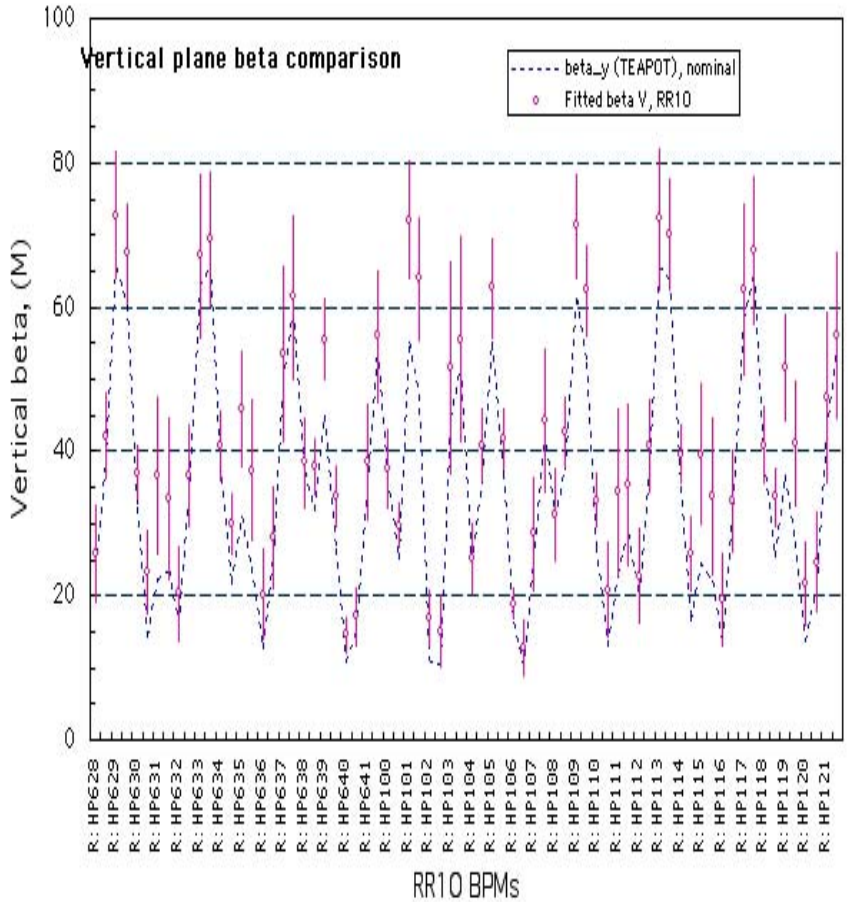
Horizontal Phase advance error by analysis of the single kick injection orbit data



Qruadrupole error of 0.6 Units in CFM

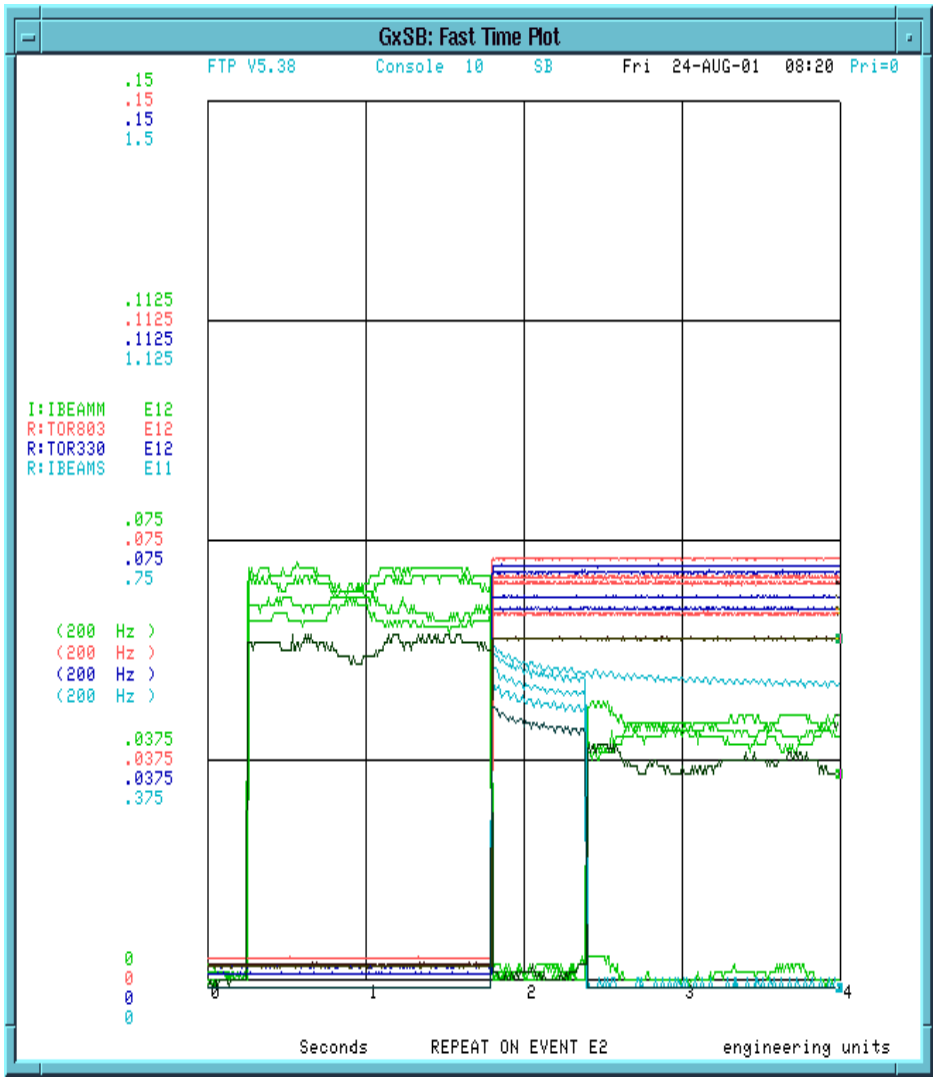
Recycler beta function measurement using Turn by Turn BPM data





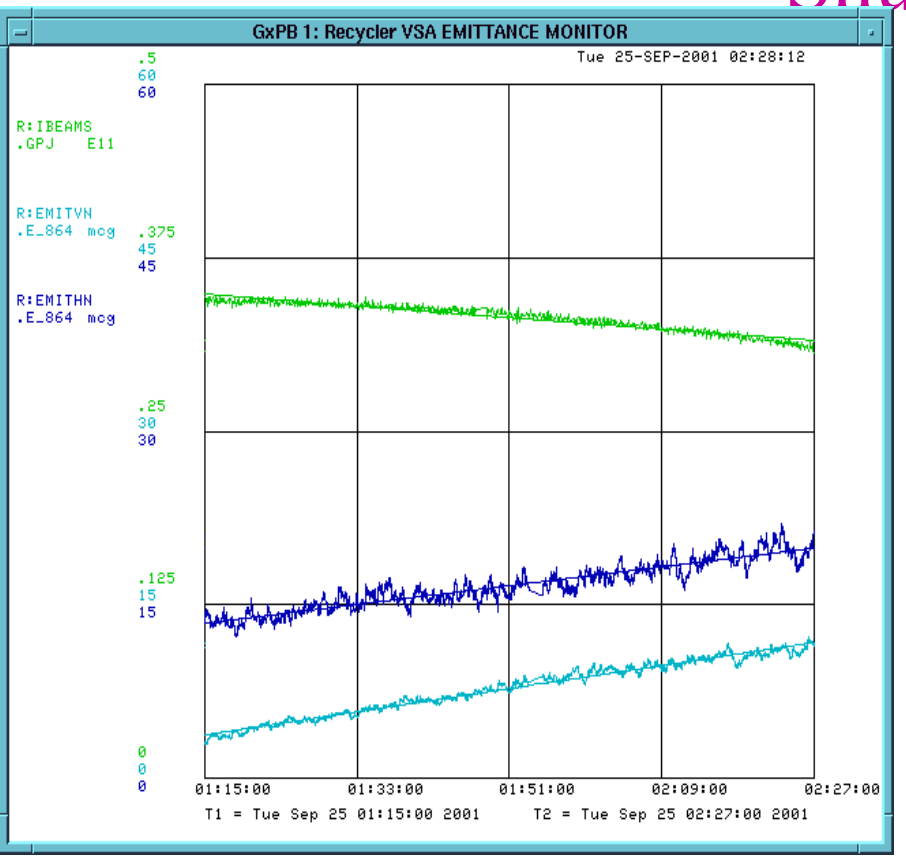
Qt302 and 307 trim quads are off. TEAPOT calculations assumes that all High beta quadrupoles are weak by 1%.

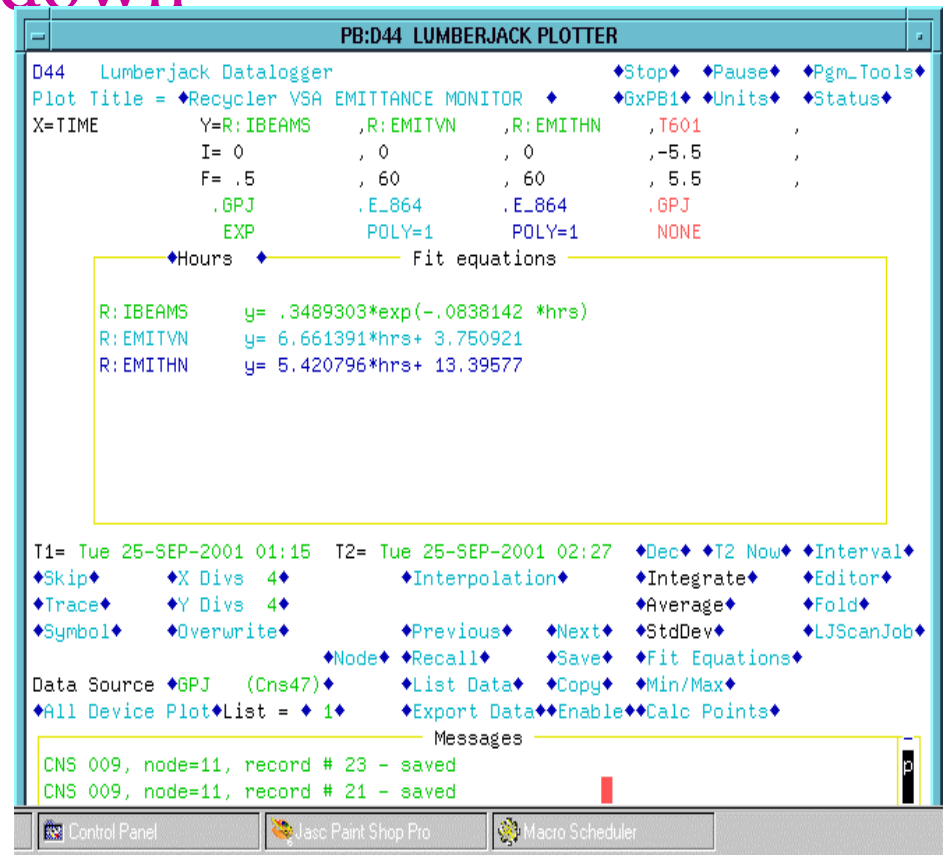
Status of the Recycler Before Nov. 01 Shutdown



- 75 % efficiency
- Poor lifetime without scraping.
- Tight Aperture in both planes.
- Measured Beta wave in the RR
- Knowledge of alignment problems
- Vacuum issues

Status of the Recycler Before Nov. 01 Shutdown





- Lifetime 12 hours with MI ramping for initial scraped beam.
- Emittance growth rate about 6 pi mm-mr/hour (calculated rate is about 3 pi mm-mr/hour based on vacuum model)

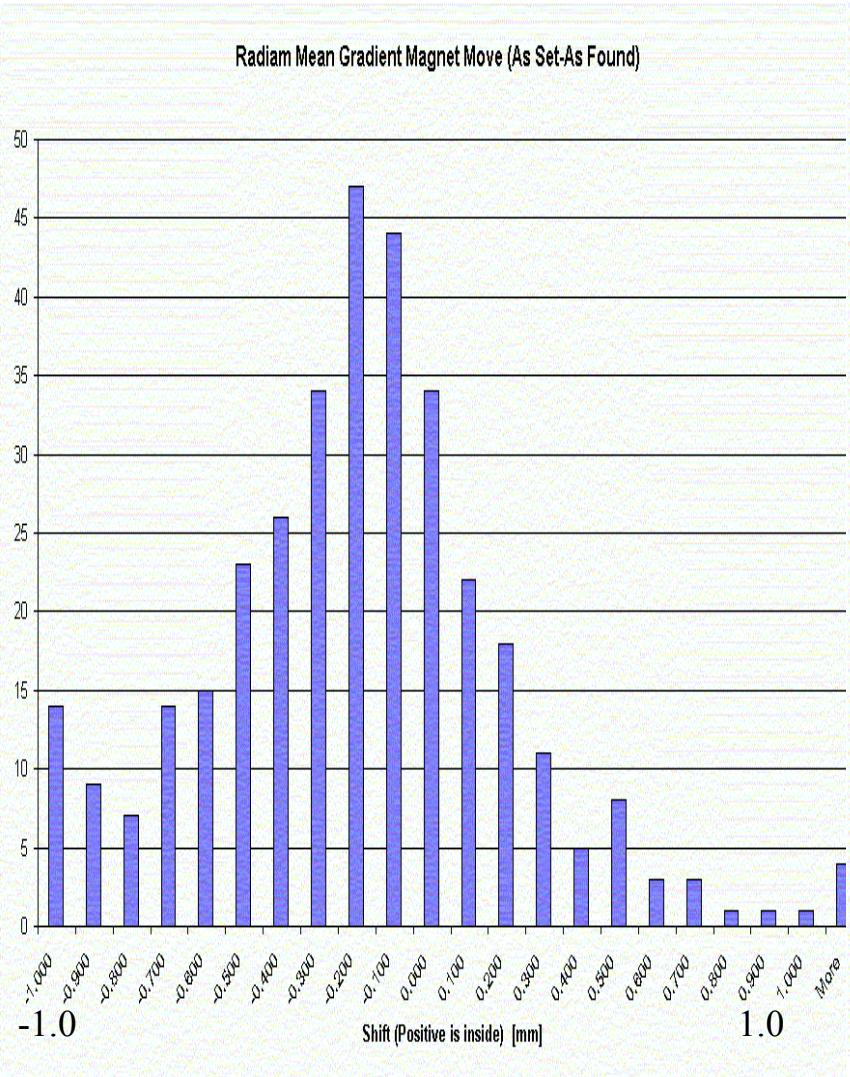
November 01 Recycler Shutdown

- Measured magnet Fudicial and aligned all Recycler magnets.
- Installed electromagnet dipole correctors at each half cell.
- Doubled the Ion Pumps in three sectors, all cables for further upgrades have been pulled.
- Installed additional quadrupoles and sextupoles
- Installed new beam pipe stands
- Installed Heater tapes inside Recycler CFM and on the beam pipe (Quadrupoles to be done later).
- Installed new calibration circuit for all BPMs and calibrated every preamps in the tunnel.
- Installed two scrapers (H and V planes)

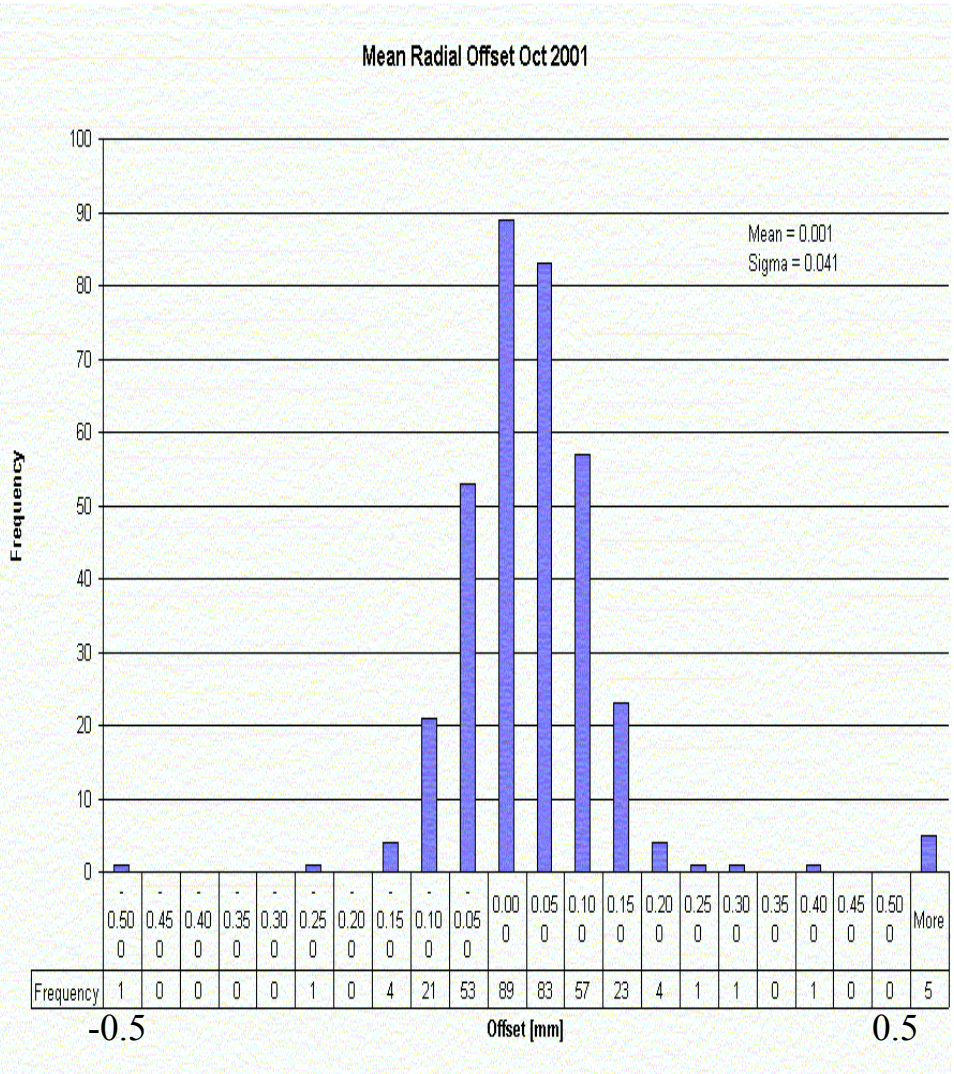
Nov. 01 Shutdown…

- Installed a new longitudinal Schottky and improved transverse
- Installed two layers of additional magnetic shielding.
- Baked two vacuum sectors
- Cooling tank reinstalled
- Removed broken heater tapes out of two CFM, 24 more to do.
- More software development for operation

Alignment of the Recycler Horizontal

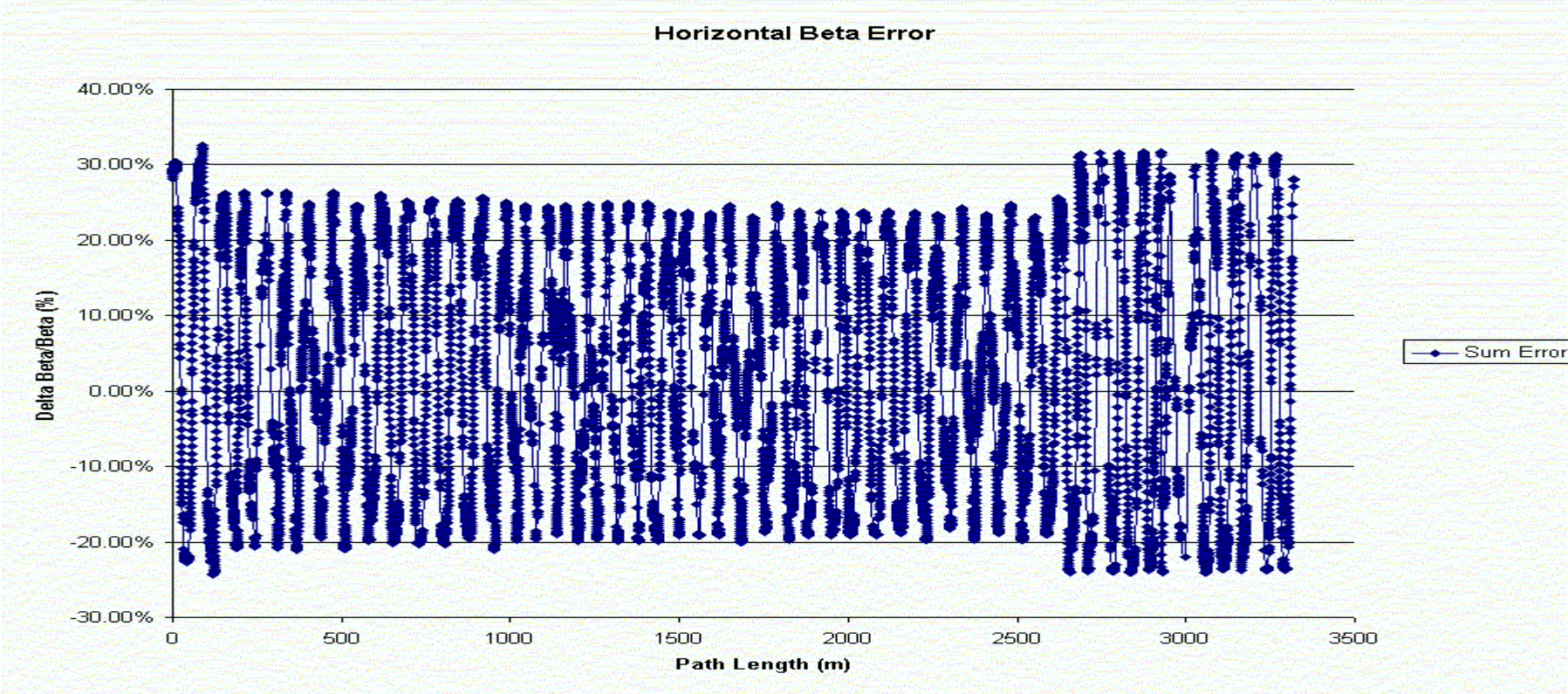


Horizontal Magnet Move



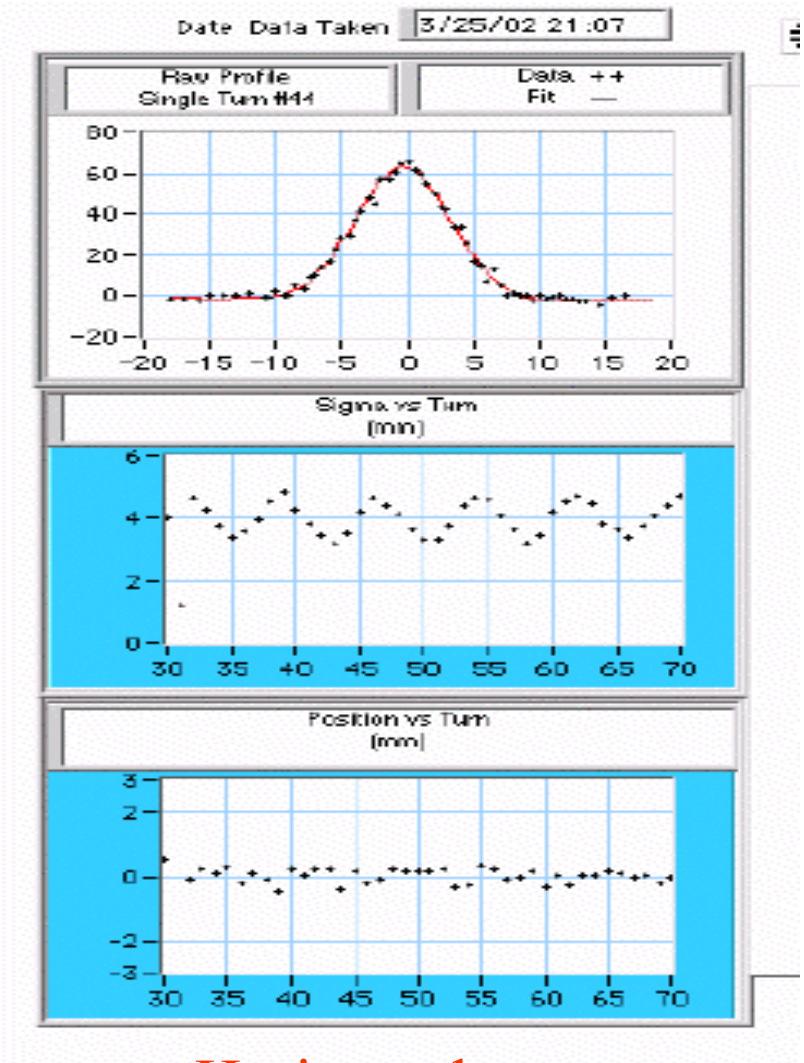
Horizontal Magnet offset

Recycler Lattice Function error (after shutdown)

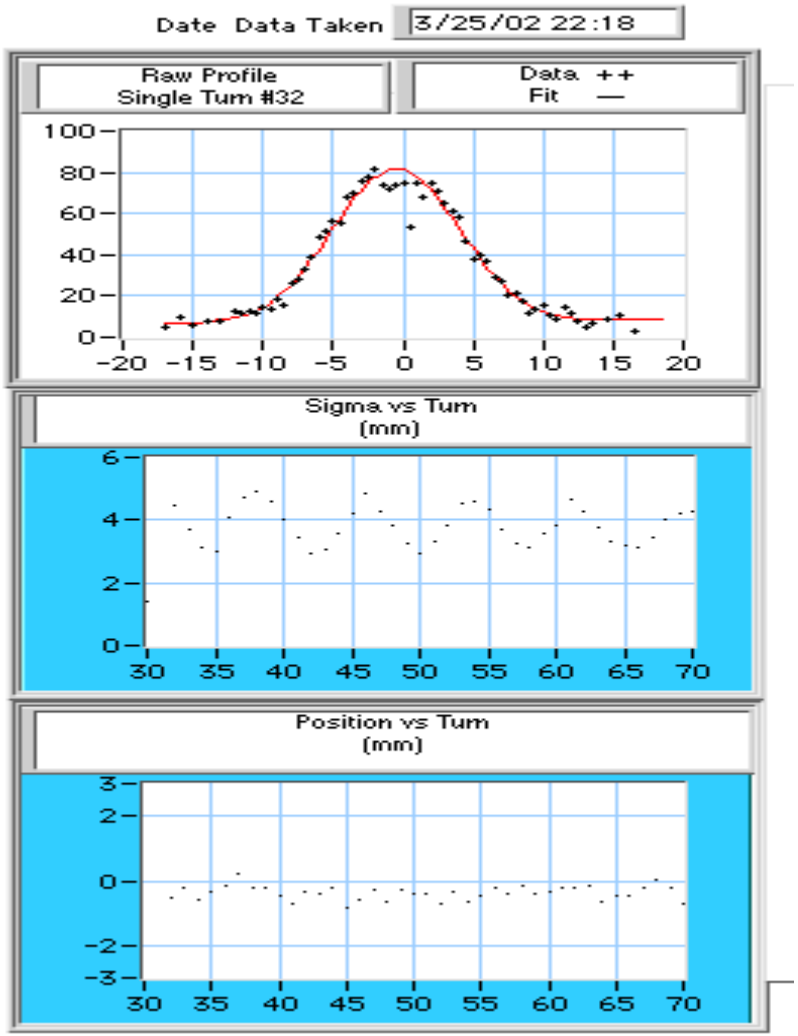


Calculated Horizontal Beta Function Error due to feed down from sextupole at injection point. Measurement agreed with this prediction.

Present Status:Injection Oscillation



Horizontal



Vertical

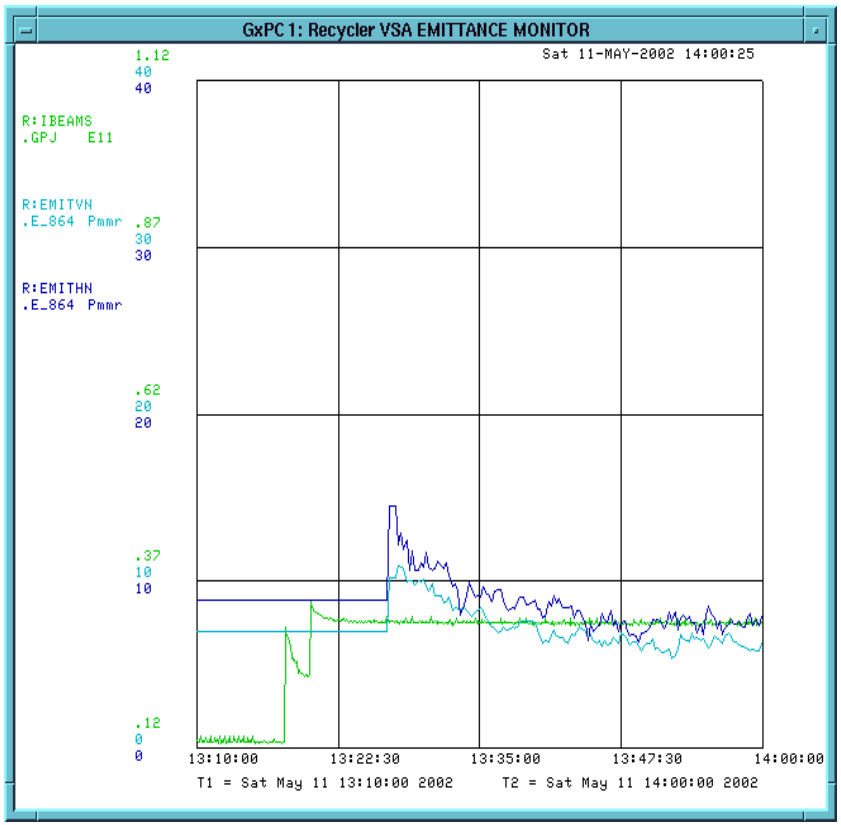
Recycler Injection…

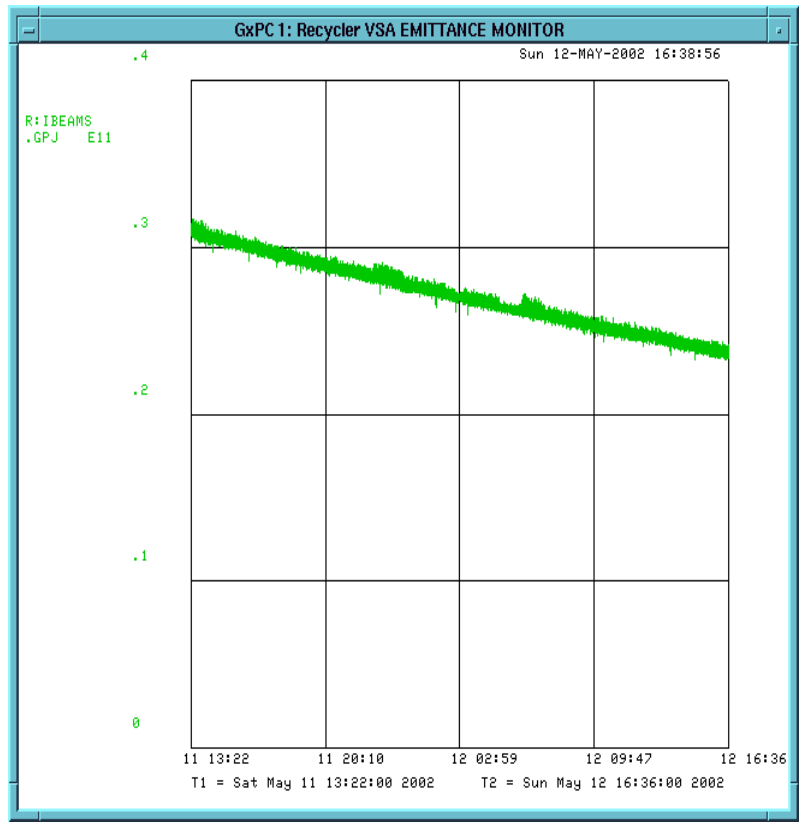
- The beam width oscillates with twice the betatron tune. This suggest possible lattice mismatch.
- This could be a potential cause of beam to grow very fast (<1000 turns) at injection.
- We found that the injection lattice functions is not matched to the circulating beam lattice functions.
- This is essentially due to feed down from the sextupole at the injection point in circulating beam.
- Lattice function of the machine needed to be fixed to the design value to improve aperture.
- Install permanent magnet trim sextupole to cancel the CFM sextupole field to fix this lattice problem (Mid Aug. 02).

Pbar transfer and Cooling

- In Jan 02 we successfully stored and cooled more than 1e11 antiprotons in the Recycler with a lifetime of greater than 45 hours. (We met a milestone)
- Since that time we have been trying to improve pbar injection, stacking and cooling in the Recycler.
- We have not perfected pbar extraction yet.
- On Feb 1st we had a small accident in the Recycler due to the uncontrolled motion of the cooling tank. This set us back by more than 12 weeks in studies.
- No beam was allowed in the Recycler till a fix to this problem was in place. After that it took several weeks to certify and commission the system.

Pbar lifetime with cooling

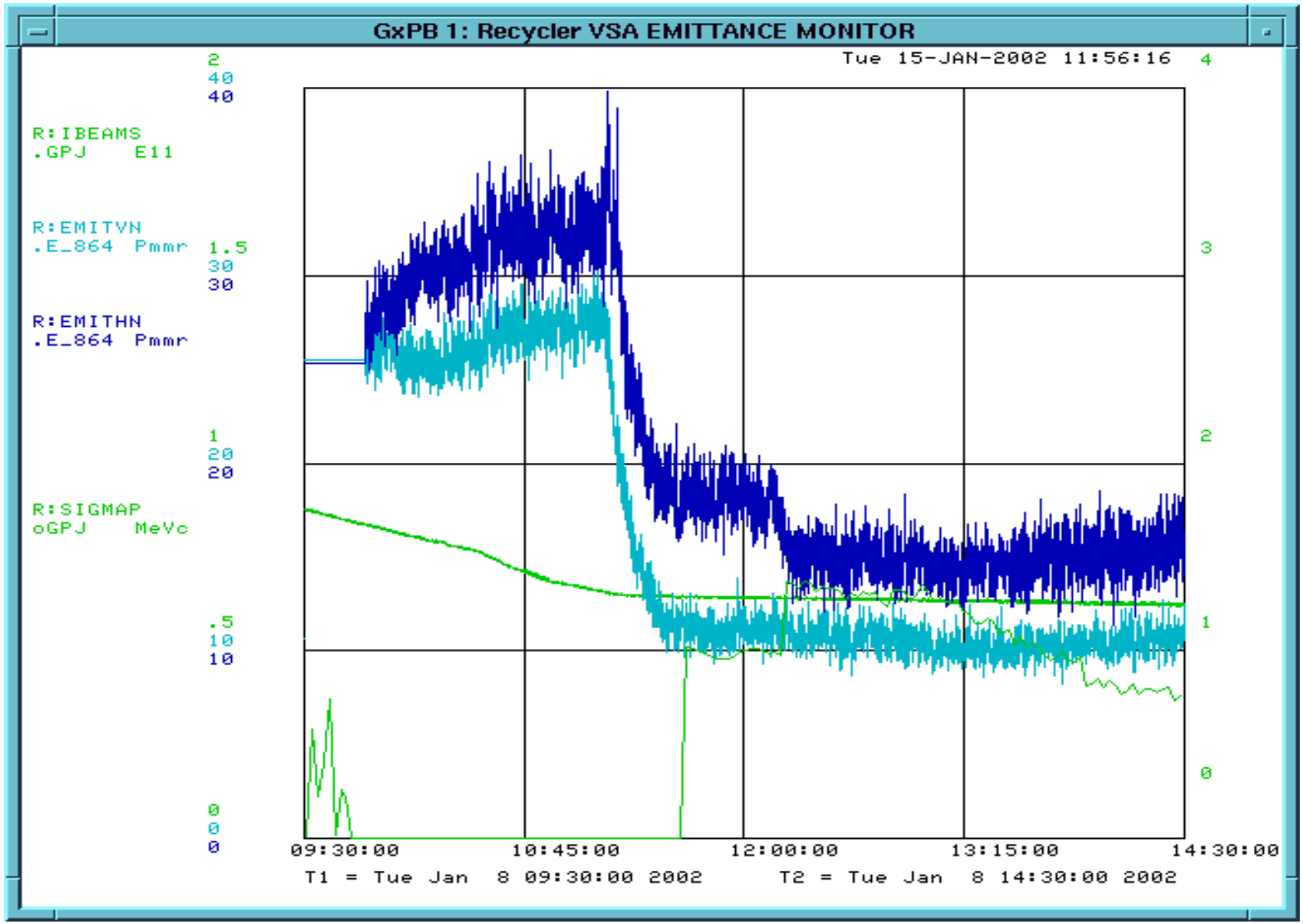




Routine transfer of pbar at the beginning of TeV store

Cooled pbar lifetime ~100 hours (3e10 pbar)

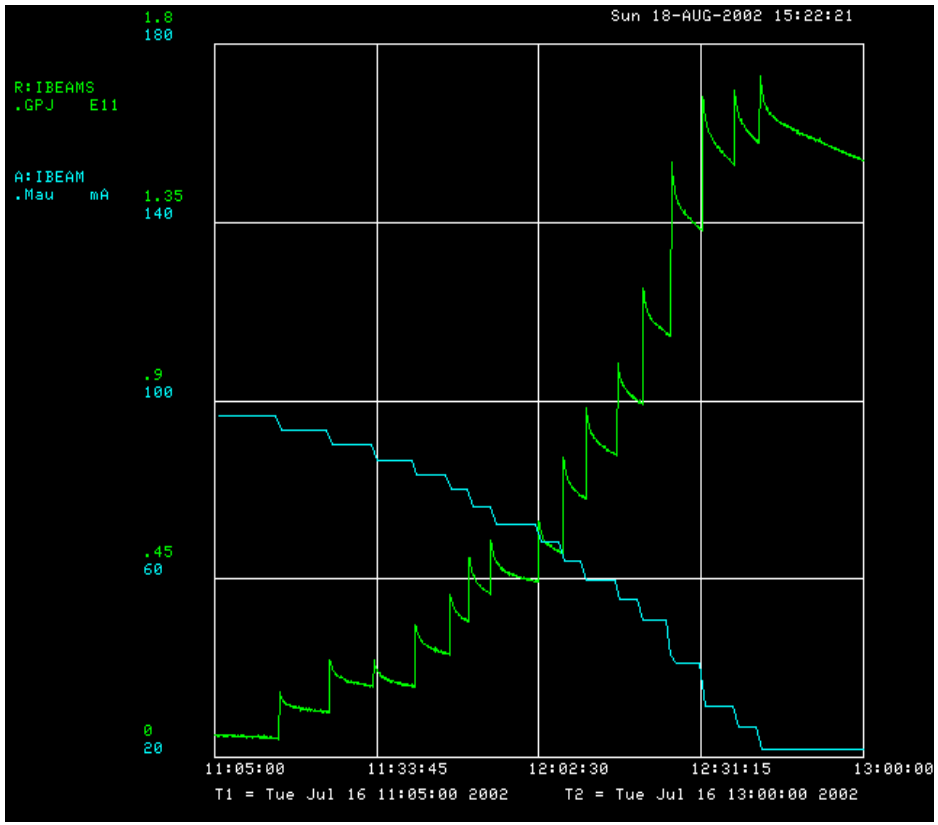
Antiproton transfer & Cooling

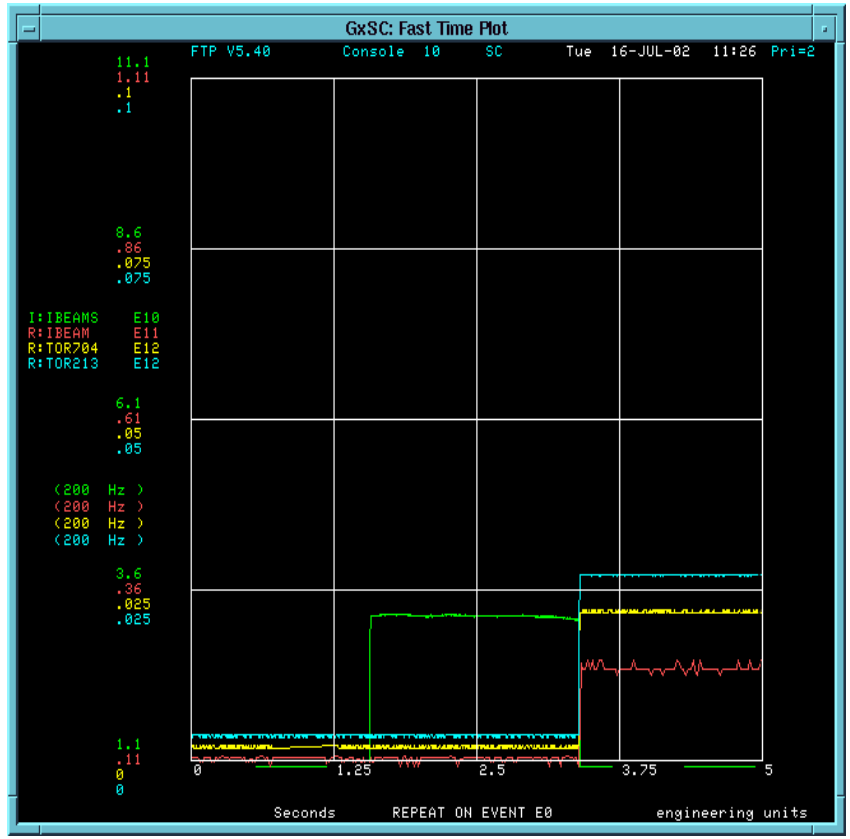


Pbar Commissioning

- pbar commissioning of the Recycler has started again after almost 3 months of no studies.
- We were mostly working on injection efficiency of pbar.
- This is due to
  - large emittance of pbar coming in to the Main Injector from Accumulator
  - Limited aperture of the injection line
  - BPM not responding to pbar signal, injection closure
- We are working on pbar extraction

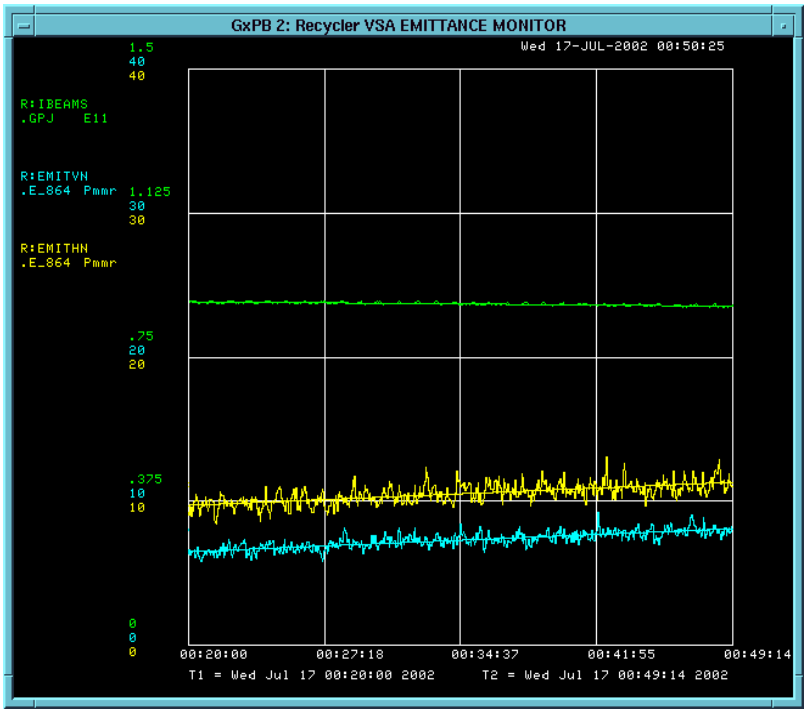
Antiproton Transfer to RR

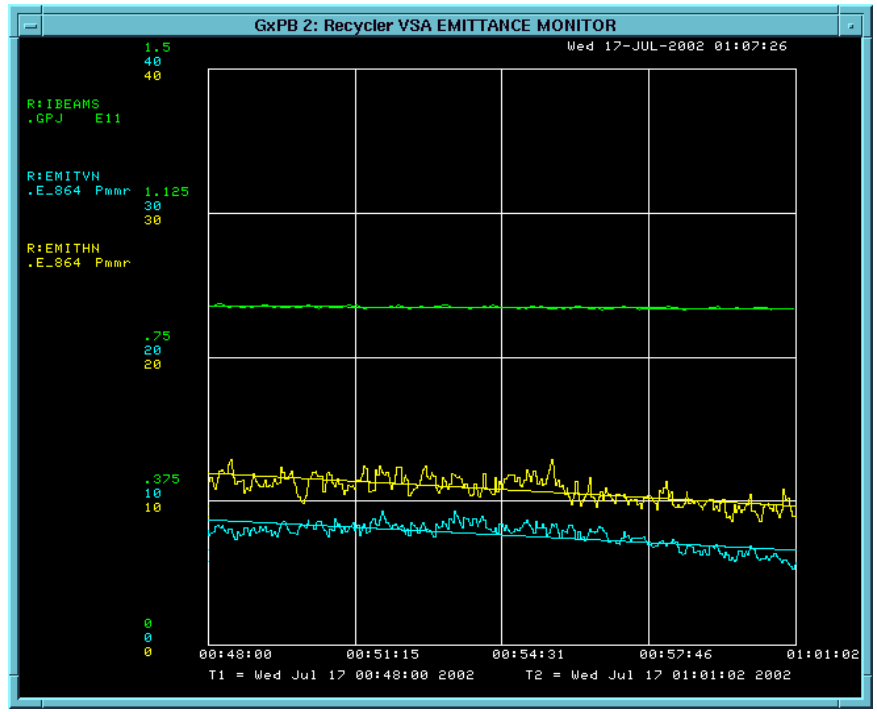




- Good injection efficiency
- Poor circulating beam efficiency
- Lifetime.

Pbar Heating and Cooling Rate





•pbar heating rate measured at this intensity is about 3-4 pi mm-mr/hour.

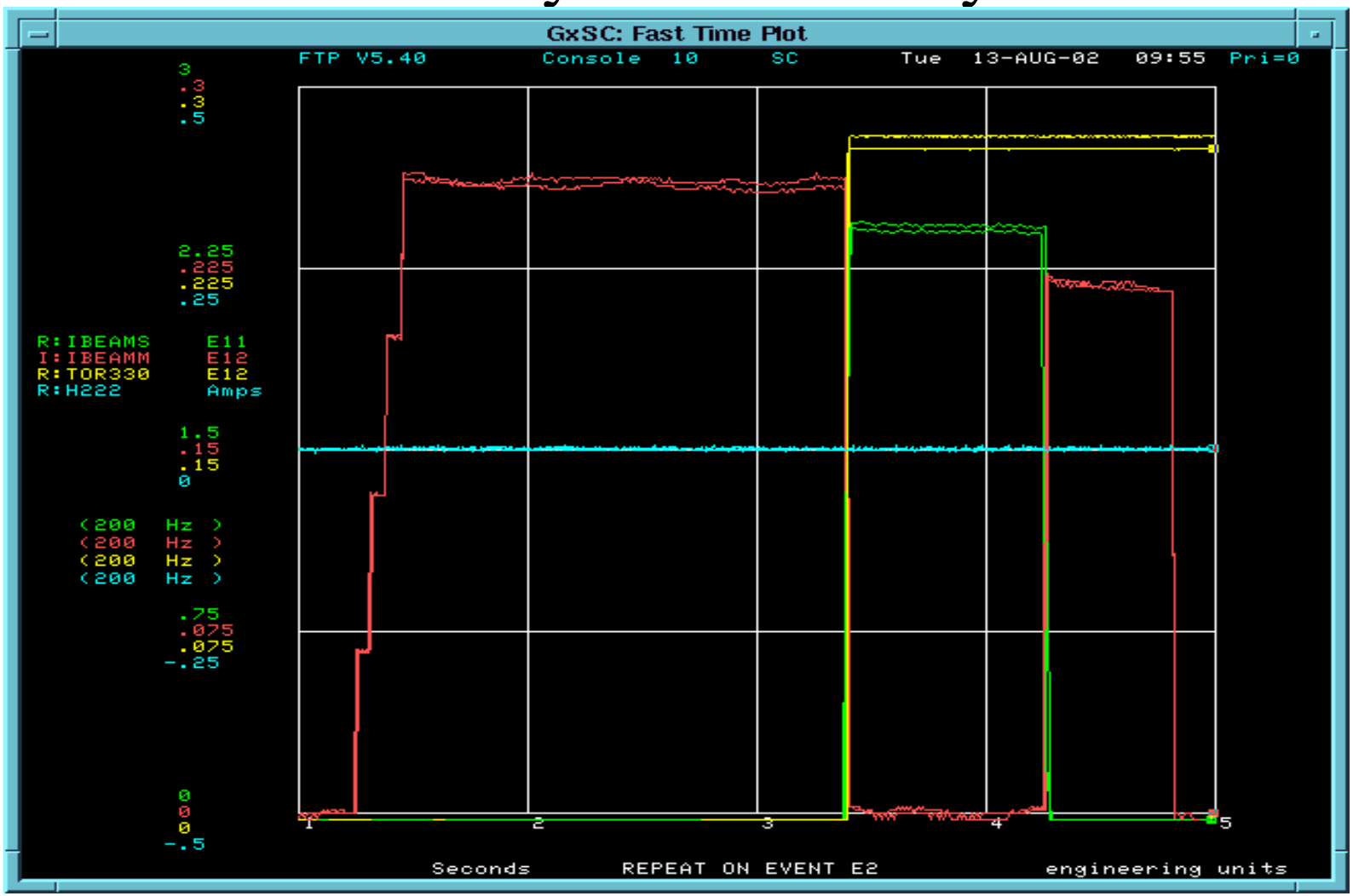
• This growth rate is similar to proton heating rate and is consistent with vacuum related growth.

The cooling rate is about 10 pi mm-mr/hour. This is not optimized yet.

Injection and Circulating lattice fixes

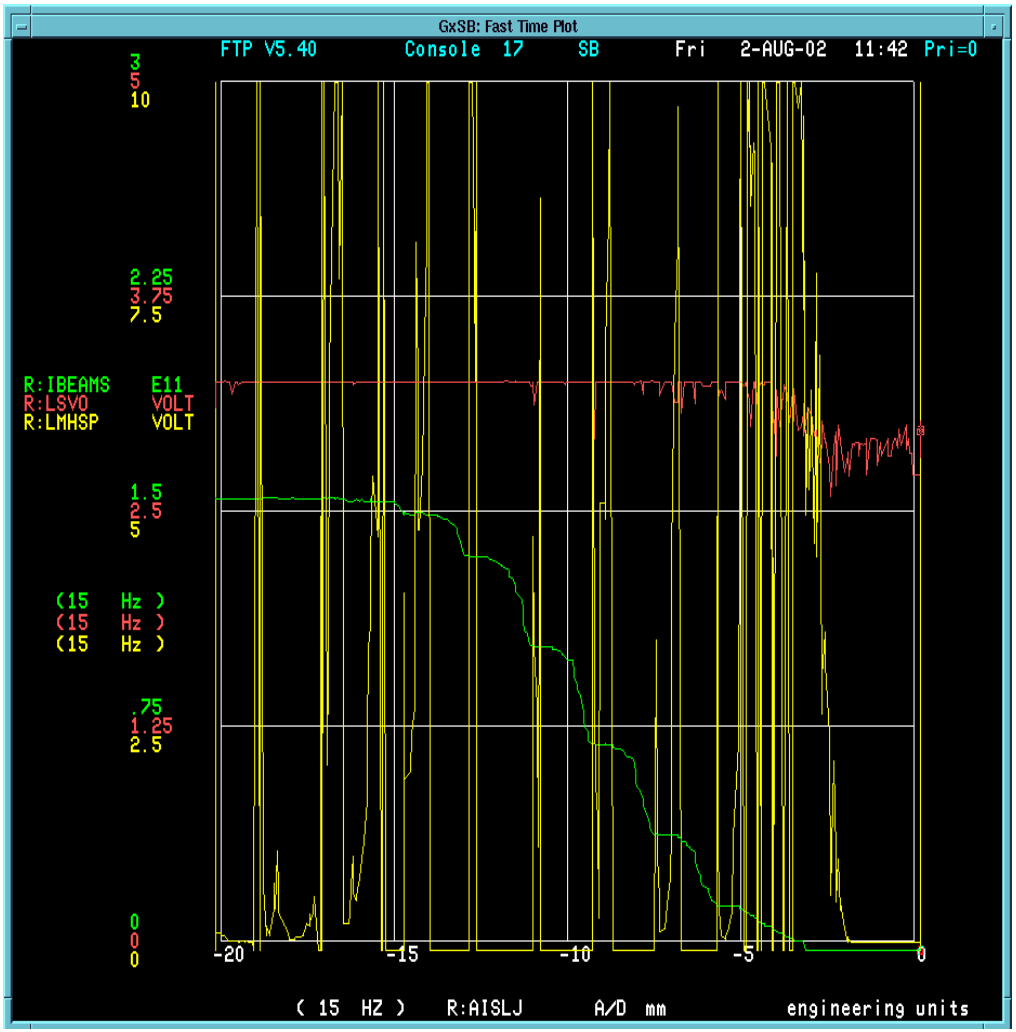
- In late Aug 02 we finished the installation of the feed down correction sextupoles at both injection and extraction locations.
- We have installed Multiwires in both the injection and extraction transfer lines.
- We have been successful in putting 53 MHz rf on to the Recycler rf cavities. Now we can inject 53 MHz beam into the Recycler, circulate and extract it in 53 MHz in the Main Injector. This allows to look at the extracted beam from the Recycler.
- Using IPM in the Main Injector, Recycler, Multiwires in both the transfer lines and 53 MHz beam capability we have been able to understand the injection much better.
- We are also working on BLT with SLAC.

Recycler efficiency



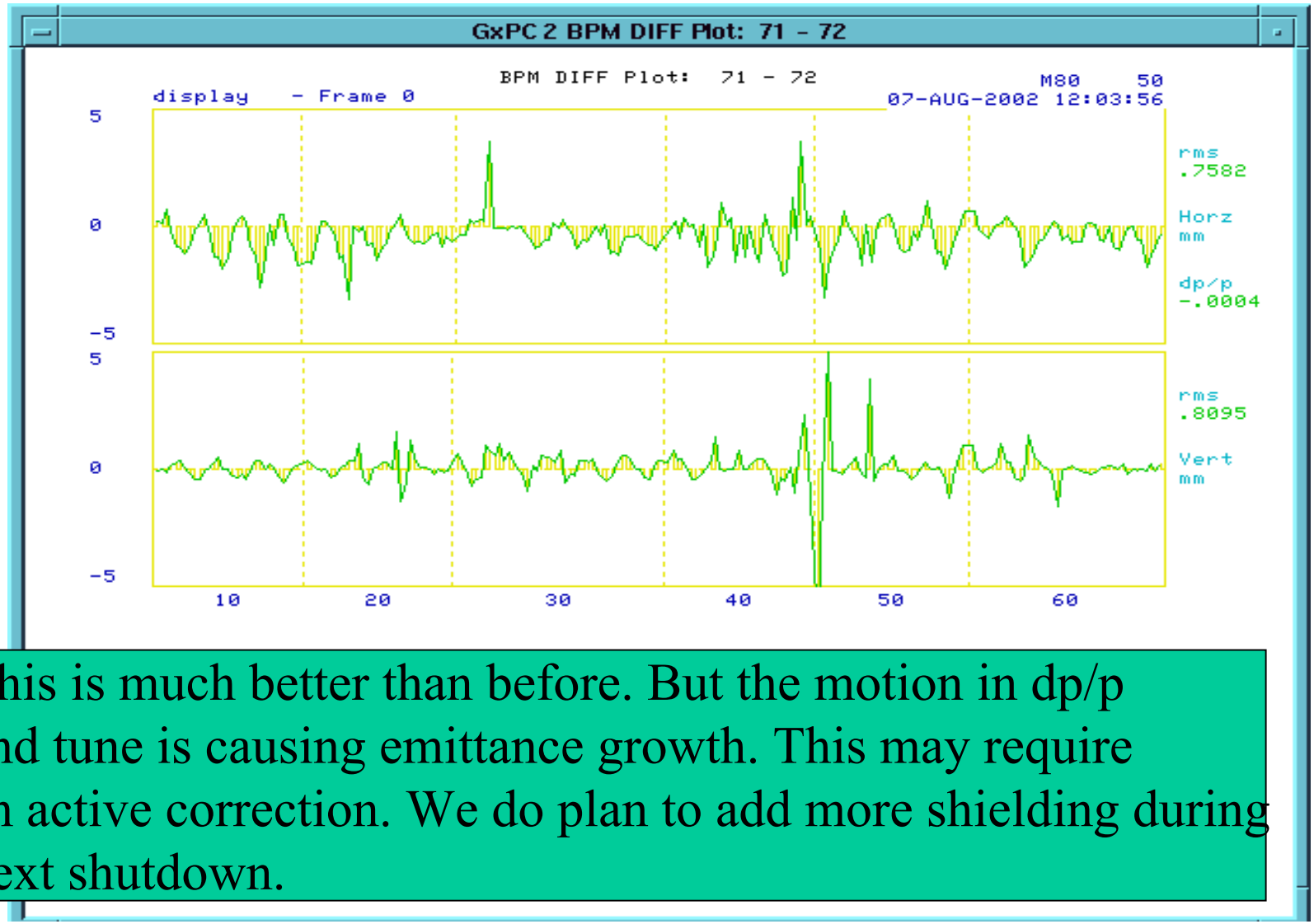
Now it is even better by about 5%.

Horizontal Aperture



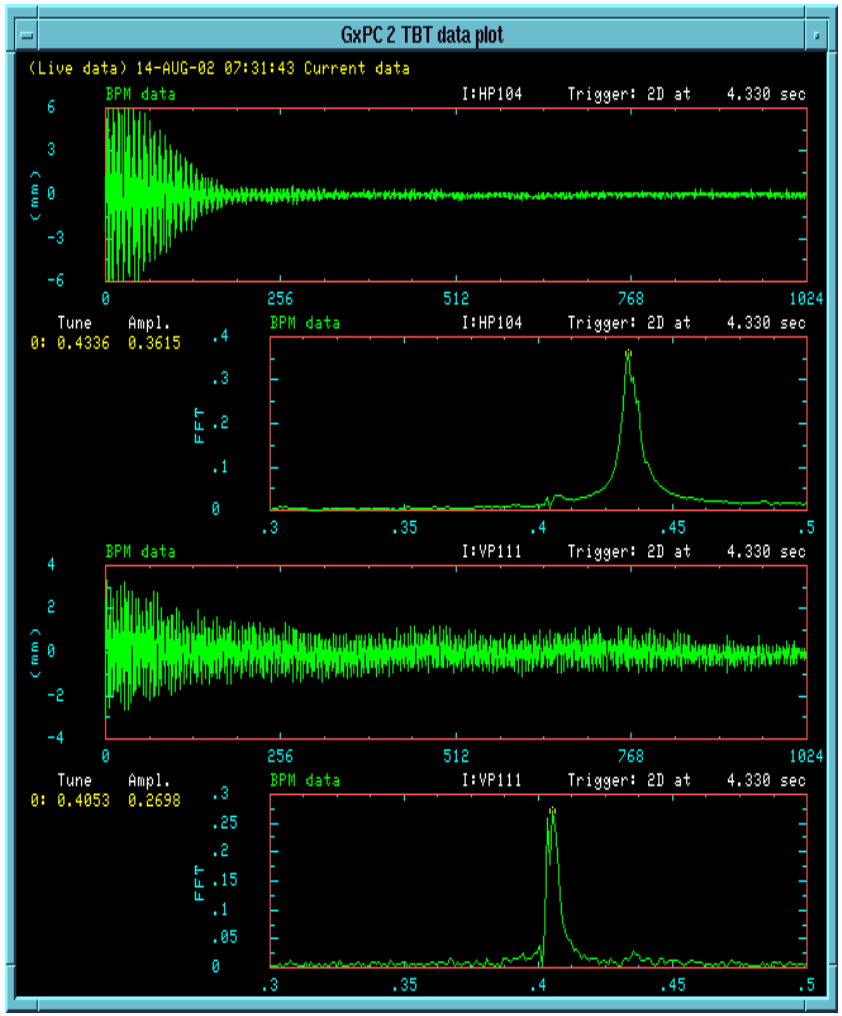
- After powering all the dipole corrector power supplies a new aperture scan was done.
- Installation of feed down sextupoles was done.
- We measured the horizontal aperture to be about 50 pi mm-mr.
- New vertical aperture is at least 40 pi mm-mr.

RR orbit motion due to MI ramp

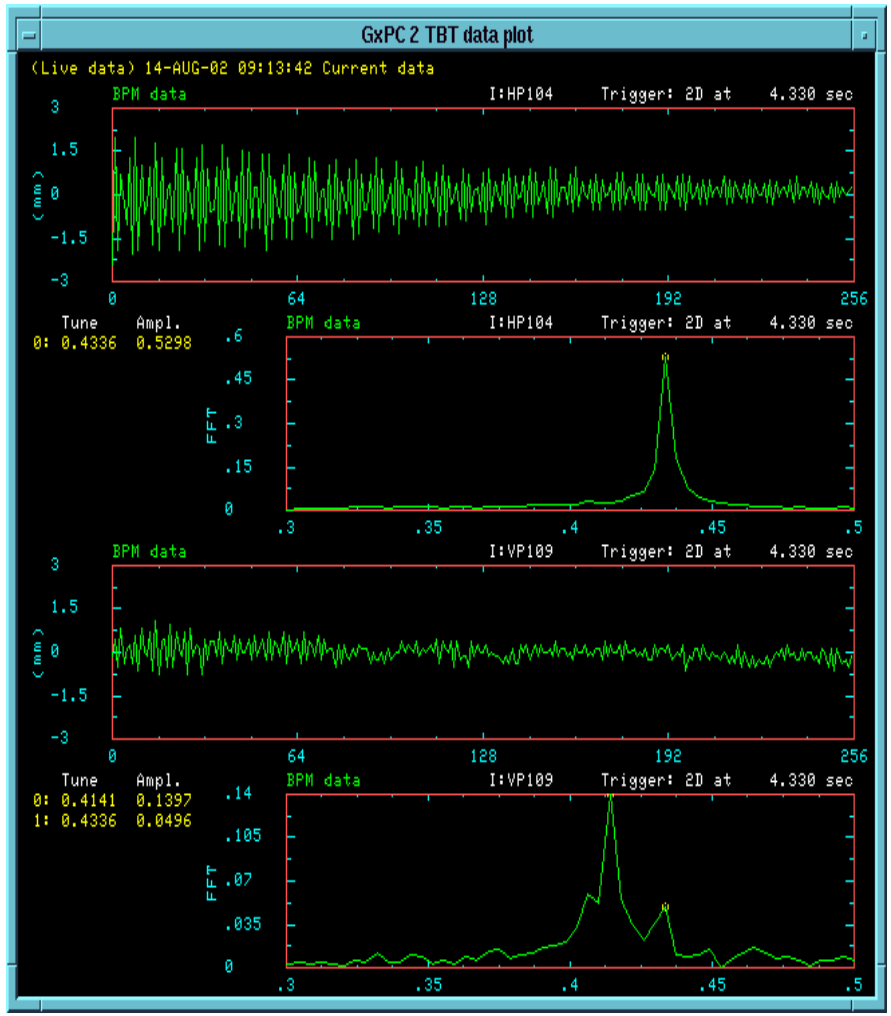


This is much better than before. But the motion in dp/p and tune is causing emittance growth. This may require an active correction. We do plan to add more shielding during next shutdown.

MI Reverse turn by turn

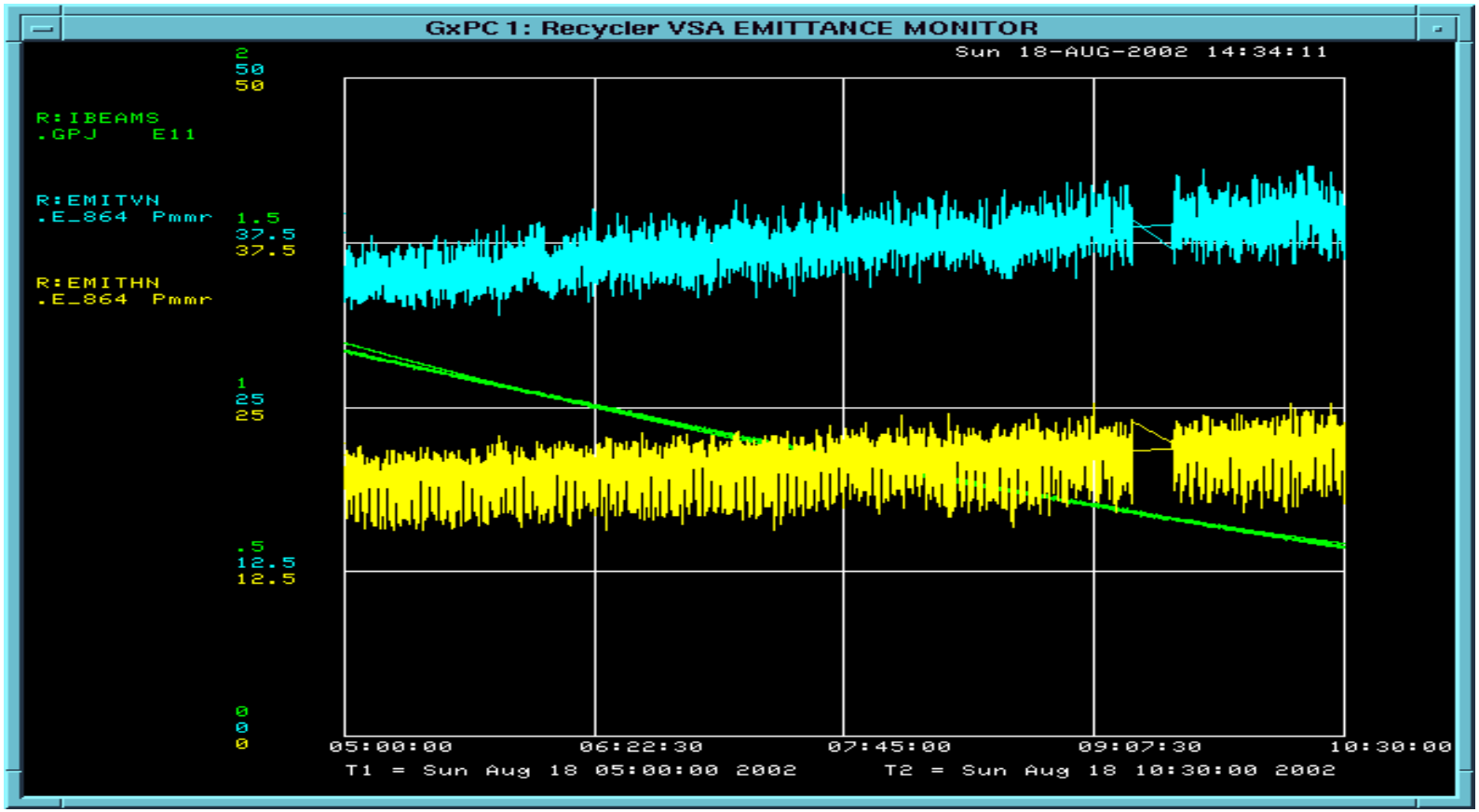


Before tuning.



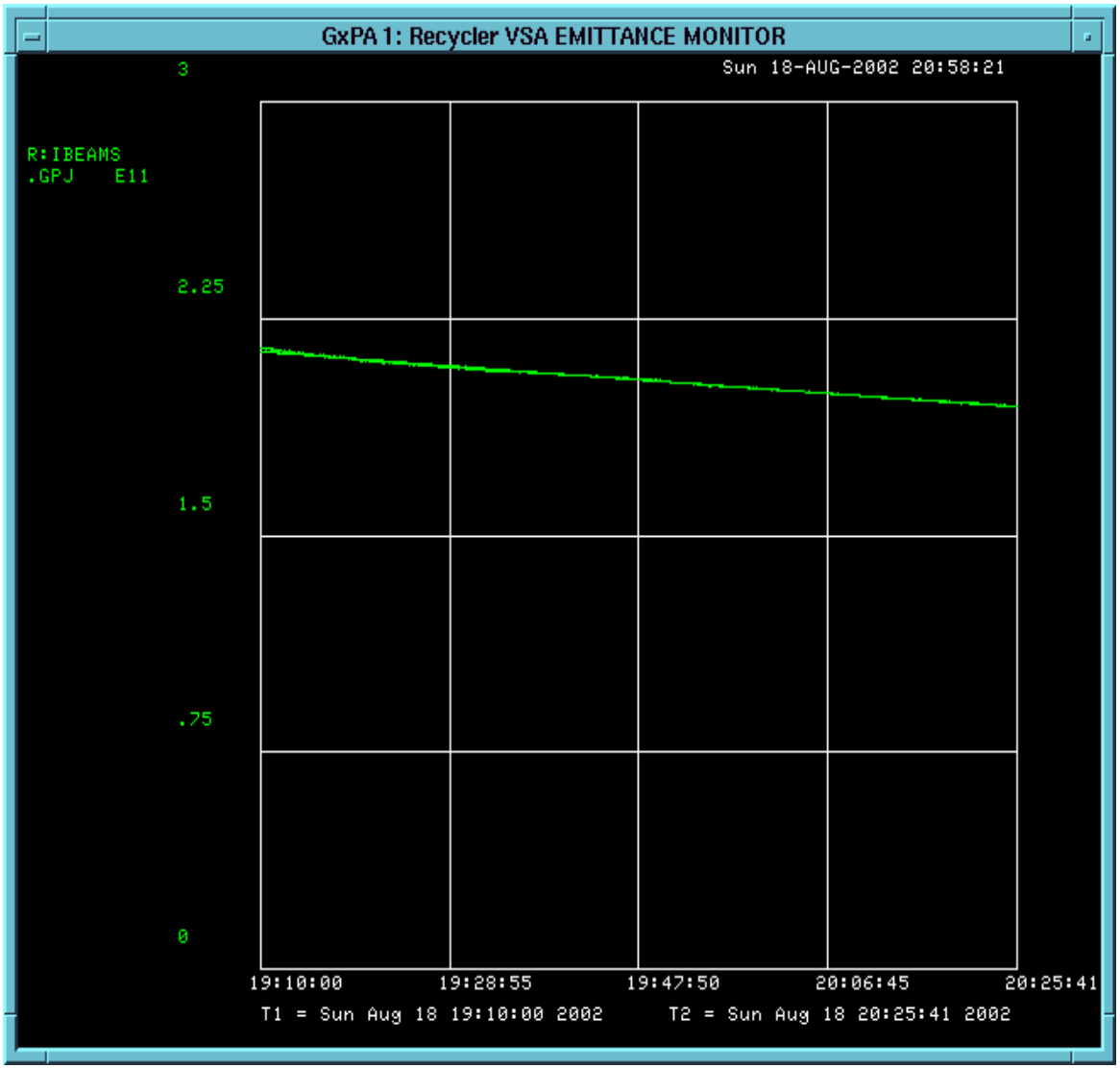
After tuning.

Recycler Lifetime



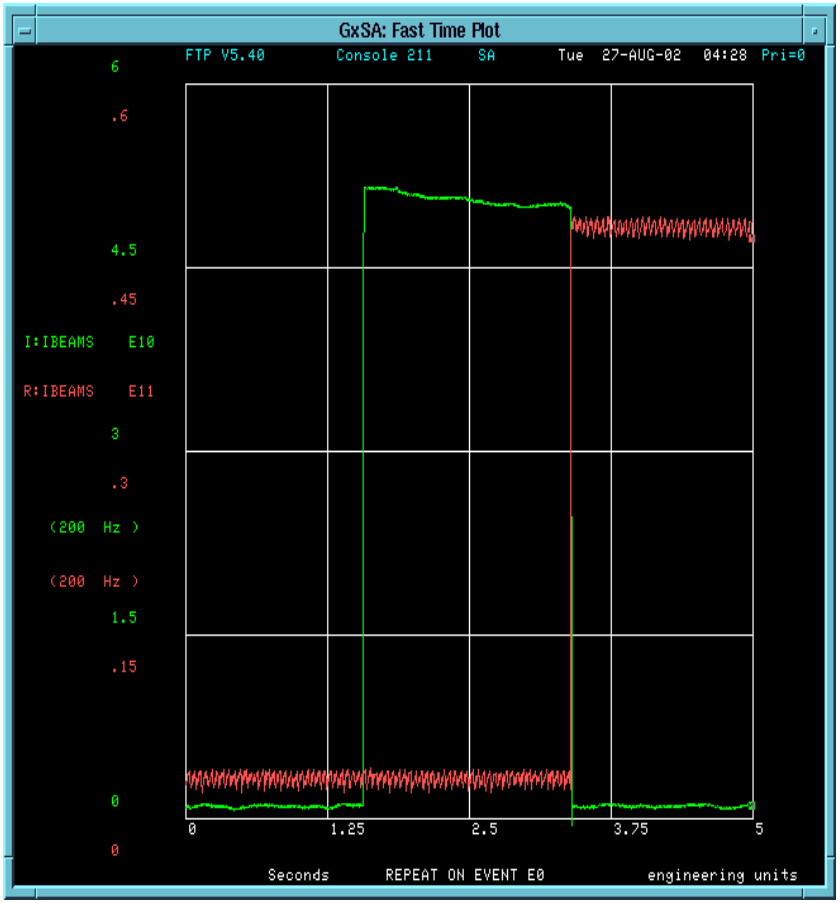
• 8 hours of lifetime for almost filled Recycler. The is the last six hours in 12 hours store.

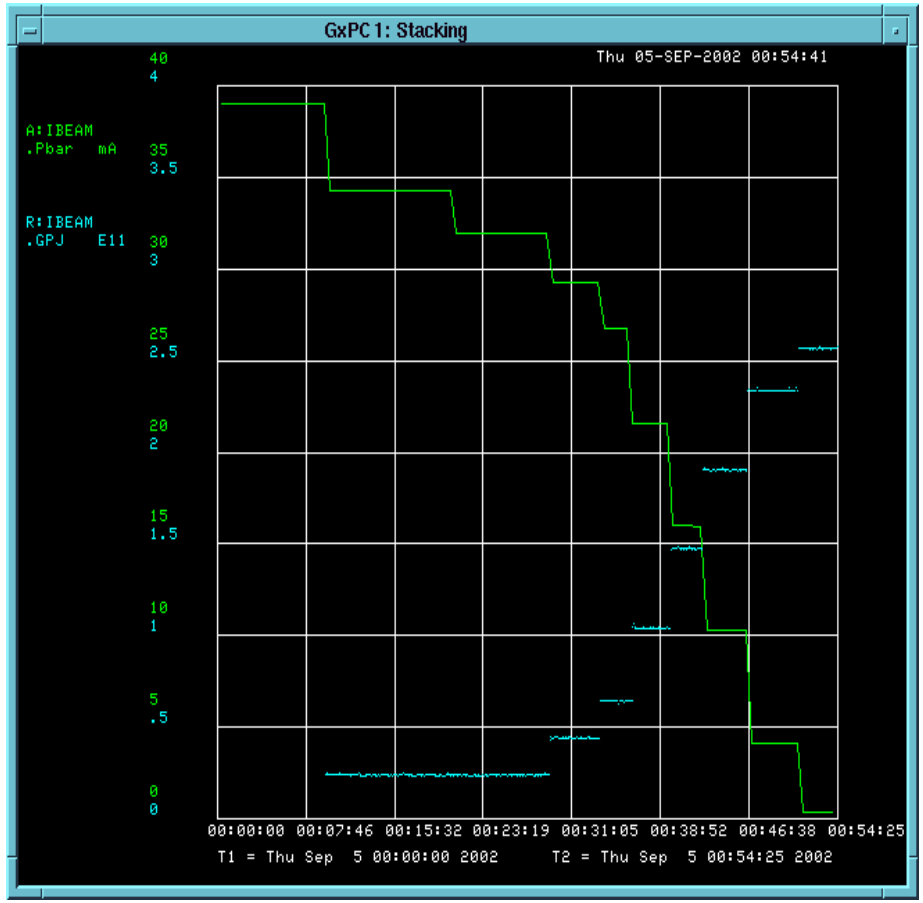
Recycler Lifetime



- Unscraped proton beam lifetime 13 hours with Main Injector ramping.
- The aperture does not fill for 2 to 3 hours with Main Injector ramp.
- This is considerable improvement.

Antiproton transfer to Recycler

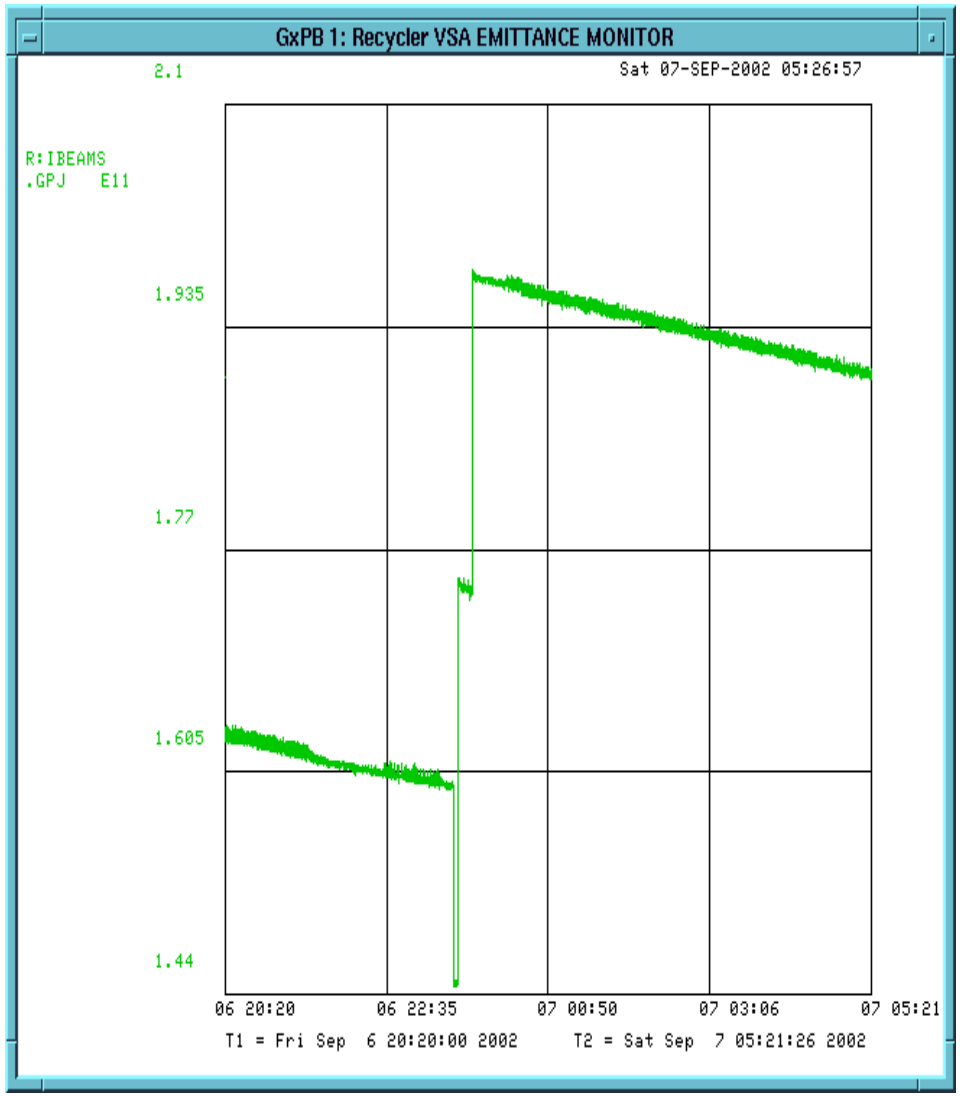




>95% circulating efficiency

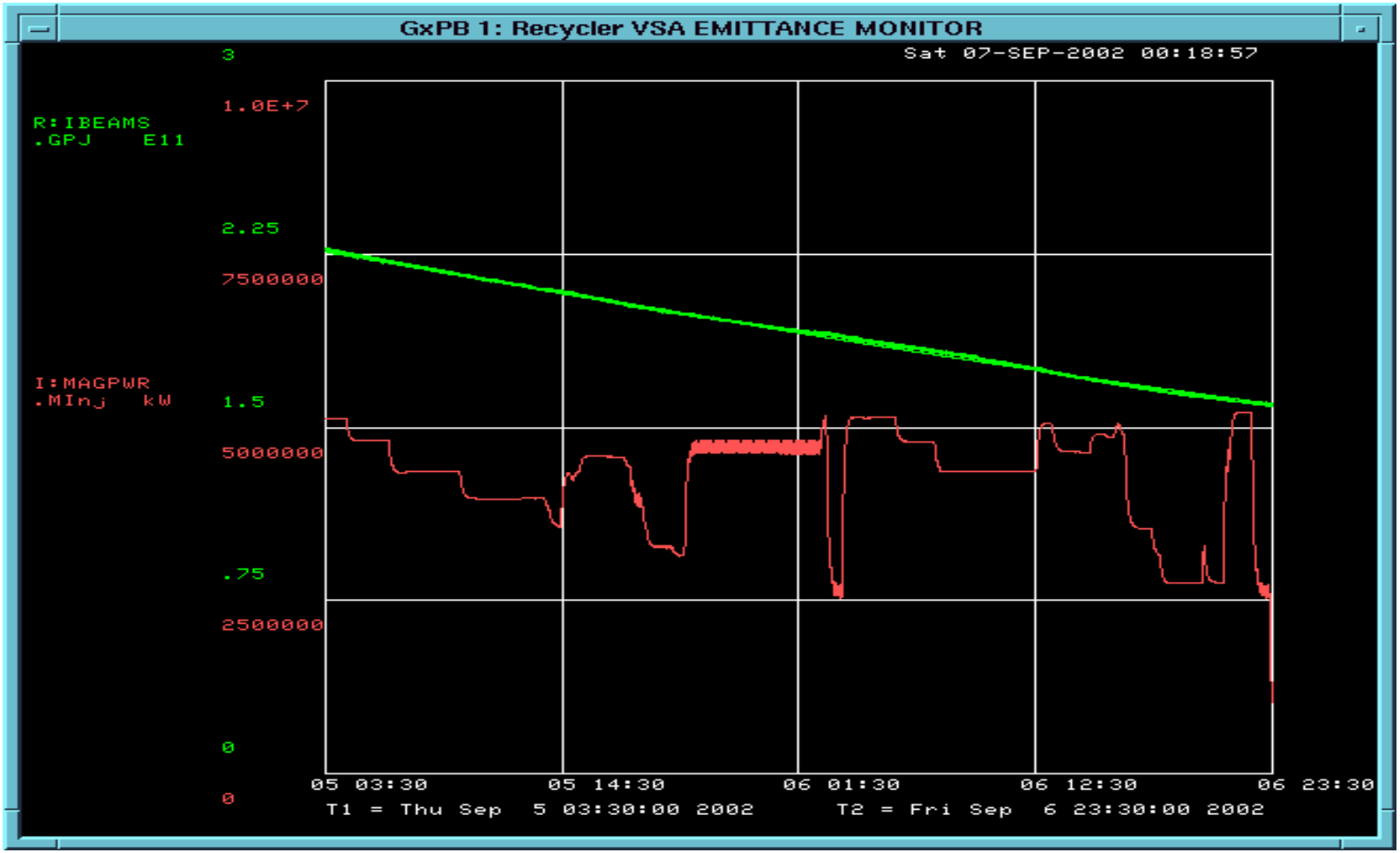
>70% stacking efficiency. This can improve to >90% (DC Beam problem)

Stacking over cooled stack



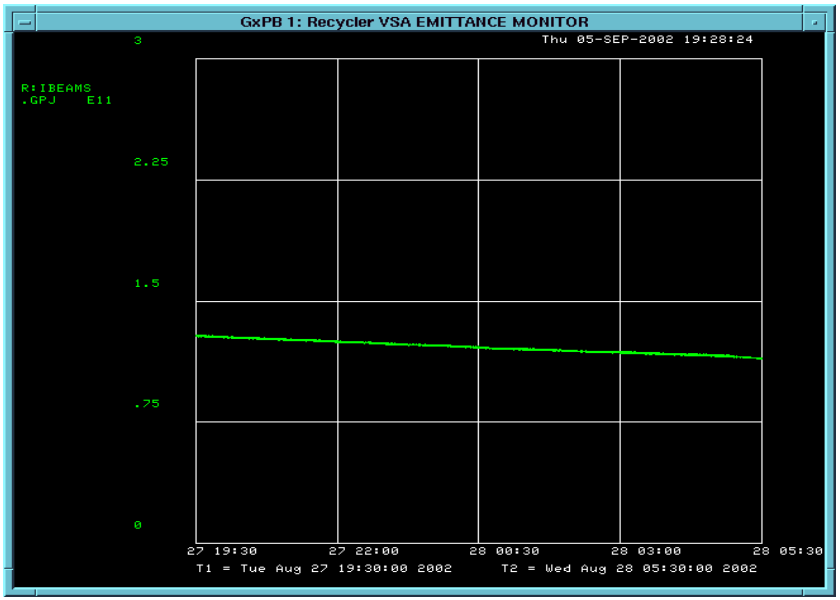
- We have made several attempts to stack new beam from Accumulator over the cooled beam in the Recycler.
- We have DC beam problem which produces some beam loss at the time of injection.
- This is being actively studied and needs RF modifications.

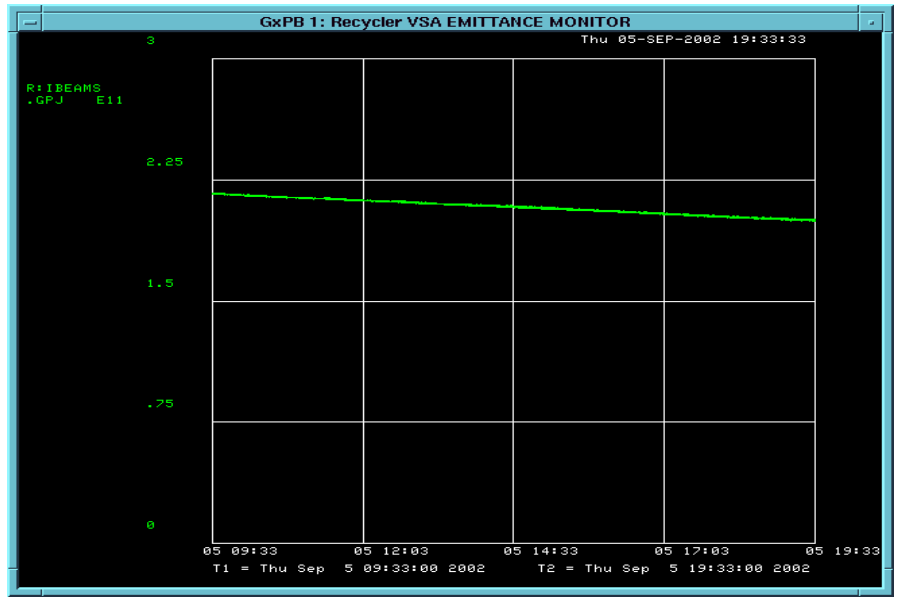
Pbar lifetime

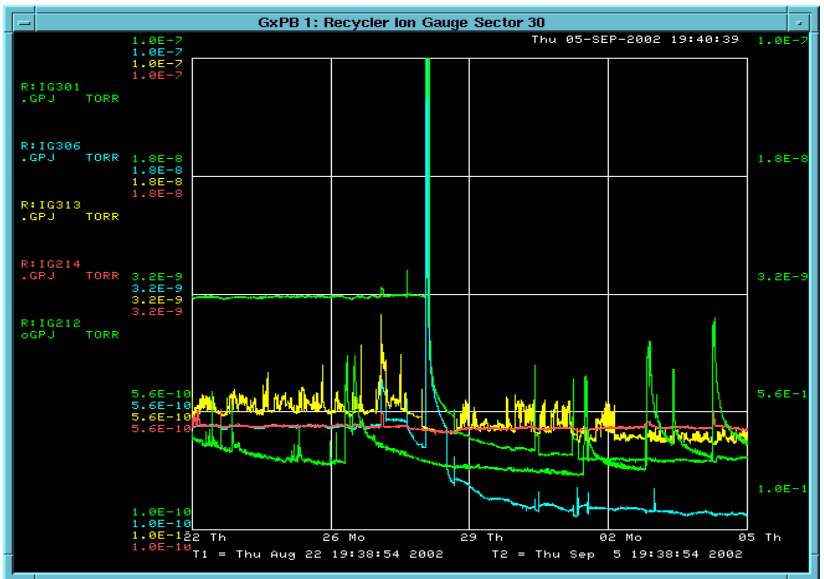


44 hours of store, 125 hours of lifetime. (Maximum stack 45e10 with a lifetime of 110 hours, cooling and operating point)

Effect of vacuum on pbar lifetime







Lifetime improved from 90 hours to 125 hours after getting the MI30 sector vacuum improved by firing TSP.

Proposed vacuum upgrade will improve this considerably.

Recycler Progress

- In last two years we have made a significant progress in the Recycler performance and its understanding.
- Recycler lifetime has improved from a few mins to > 10 hours without cooling for protons.
- Recycler efficiency has improved from 25% to >90%
- Injection emittance growth is smaller.
- The Stochastic cooling system has been commissioned with pbar. We have measured a cooling rate of 10 pi mm-mr/hour. When the heating rate is about 4 pi mm-mr/hour.
- pbar lifetime of >100 hours has been observed for 40e10 pbar.
- Yet we are not done.

Recycler Goal

- 2e12 (5e12) antiproton stored in the Recycler.
- Transfer efficiency > 95% and Stacking efficiency > 90%
- Lifetime larger than 100 (200-300) hours with cooling for 2e12 antiprotons.
- Equilibrium emittance < 10 pi mm-mr.

Issues

- Resources
  - We have several technical issues which needs physicists and engineering help. We know the problem but it is taking much longer than one expect to find a solution.
  - We have a serious lack of experts. I have taken the maximum number of young physicists in the department. They need to take charge but it will take some time.
  - Recently Peter Limon has joined the group. He is heading the Recycler Shutdown work. He has put together an impressive group of staff from around the laboratory to help this project.

Physics Issue

- Injection and circulating Efficiency for proton and pbar is about 95%
- Emittance growth is about a factor of 4 larger than the design. Significant fraction of this could be vacuum related.
- Recycler performance is seriously effected by the Main Injector ramp.
- Circulating and injection lattice and aperture
- Operational point of the Recycler is very sensitive to the machine orbit.
- Cooling needs to be optimized
- RF manipulations needs to be optimized.

Technical Issues

- Instrumentation
  - Beam Position Monitor
  - Beam Line Tuner
  - Flying Wire
  - Ion Profile Monitor (Physics Understanding)
  - Schottky Detector
  - Injection Damper
  - Reliable and operational Instrumentation
  - More RF power

Technical Issues…

- We need to develop several software to support new hardware being placed in the Ring.
- We also need to develop several software for operation and physics analysis.
- Accumulator to Recycler transfer
  - We need to redefine the 8.9 GeV/c for the complex. The best solution is that we readjust the Accumulator momentum.
  - We are proposing that all transfer takes place in 2.5 MHz.
  - We need to define the transfer frequency and frequency jump MI have to do.
  - We must push ahead on using MI as a transfer line.

Upgrades of the Recycler

- Vacuum upgrades
  - Double ion pump in the Recycler
  - Install insulator inside the CFM for higher temperature bake.
  - Bake at a higher (>110 deg C) temperature for 4 days.
  - Install more gauges and RGA
- Instrumentation Upgrade
  - BPM Upgrade for the MI complex
  - Upgraded IPM and Schottky detectors
- Injection Dampers
- Beam Loading and RF noise reduction

Upgrades of the Recycler…

- Continued study of injection aperture, improvement and/or replacement of injection lines.
- Better RF manipulation and control of emittance growth. More RF power will be required.
- Stoshastic cooling system optimization, upgrades
- Software
- We need to continue Recycler beam studies to refine our upgrade plans.

Summary

- Over the last year we have made significant progress in the Recycler performance.
  - Recycler circulating antiproton beam efficiency >95% and stacking efficiency of about 70% has been achieved.
  - Antiproton lifetime >100 hours for >40e10 pbar.
- We still have several issues related to RF manipulations at stacking and extraction.
- We need several instrumentation upgrade to understand the Recycler better.
- Recycler is very close to being a operational machine.
- The proposed Recycler upgrade will make the Recycler fully operational.